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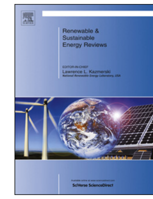

Toward aerogel based thermal superinsulation in buildings: A comprehensive review

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ABSTRACT

Aerogel is a kind of synthetic porous material, in which the liquid component of the gel is replaced with a gas. Aerogel has specific acoustic properties and remarkably lower thermal conductivity (≈ 0.013 W/m K) than the other commercial insulating materials. It also has superior physical and chemical characteristics like the translucent structure. Therefore, it is considered as one of the most promising thermal insulating materials for building applications. Besides its applications in residential and industrial buildings, aerogel has a great deal of application areas such as spacecrafts, skyscrapers, automobiles, electronic devices, clothing etc. Although current cost of aerogel still remains higher compared to the conventional insulation materials, intensive efforts are made to reduce its manufacturing cost and hence enable it to become widespread all over the world. In this study, a comprehensive review on aerogel and its utilization in buildings are presented. Thermal insulation materials based on aerogel are illustrated with various applications. Economic analysis and future potential of aerogel are also considered in the study.

Contents

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1. Introduction

Warming of the Earth's atmosphere and oceans is unequivocal. Earth's average surface temperature has increased by about 0.8 °C and approximately two thirds of this increment has occurred over just the past three decades [1]. Today, there is a consensus among scientists that global warming is primarily caused by increasing concentrations of greenhouse gases produced by human activities such as the burning of fossil fuels and deforestation [2,3]. Climate model projections indicate that during the 21st century the global surface temperature is likely to rise a further 1.1–2.9 °C for their lowest emissions scenario and 2.4–6.4 °C for their highest [2]. These predictions force the world to rethink global energy strategies and consequently take appropriate measures [4]. In this regard, intensive efforts have been made especially in recent years for public awareness on carbon footprint, the trend of carbon dioxide (CO_2) concentration in the Earth's atmosphere [5] and its effects on global climate [6,7]. The necessity of the stabilization of atmospheric CO_2 concentration below 500 ppm has been often underlined [8]. As a result of the international political efforts, a strong stimulation of research into renewable energy technologies has been observed throughout the world especially in the last decade [9,10,58–62]. The main goal of those studies was to narrow the gap between conventional and renewable energy sources due to the growing significance of environmental issues [11–17]. Currently, renewable energy resources supply about 14% of total world energy demand and their future potential is remarkable [18,19]. However, this notable progress is not still sufficient for the urgent stabilization of greenhouse gas concentration in the atmosphere. Therefore, research on energy management and efficient minimization of energy consumption has become vital more than ever in recent years. By the end of the 20th century European Union decided to accept Kyoto-protocol about to decrease the emissions. It was planned to reduce emissions 20% in 2020 compared to the emission levels of 1990 [20].

In the early 21st century, there was an indisputable necessity for the world to recheck the energy consumption levels and their distribution by sector. In 1999, total energy consumption in Europe was reported as 1780 million tons of oil equivalent and 35% of this amount was consumed by residential and commercial sector [21]. One year later, total energy consumption of the United Kingdom by sector and by building type was specified as illustrated in Fig. 1. It was concluded from the report that buildings have a major impact on total greenhouse gas emissions in Europe [22]. Baetens et al. [23] also reported that buildings emitted 8.3 Gt CO_2 in 2005 accounting for more than 30% of the greenhouse gas emissions in many developed countries. In this respect, utilization of traditional insulation materials is regarded as a solution to abate the greenhouse gas emissions in the atmosphere. For instance, Chitnis et al. [151] have evaluated the effects of energy-efficient improvements on potential energy and emission savings for UK households, and they have concluded the average UK property would achieve a 5.5% reduction in greenhouse gas emissions by using wall insulation. However, conventional insulation materials are used in thicker or multiple layers in order to obtain the desired conditions and this situation causes dramatically heavier constructions and complex building details [24]. On the other hand, there is a consensus among scientists that air as an insulator had reached its limit [25,26], and hence developing new, high performance insulation materials is a crucial need for the insulation market. Therefore, several attempts have been made to develop novel thermal insulators meeting the requirements of superinsulation theory.

Although yet discovered in the 1930s [27,28], aerogel as a thermal superinsulation material has undergone great progress and changes in recent years. Aerogel has attracted different sectors and thus it had a wide range of application areas including buildings, automotive, electronics, clothing, etc. Due to its superior physical and chemical characteristic features, aerogel has won great interest especially for energy-efficient retrofitting opportunities of residential buildings [29]. The market share of aerogels tripled to 83 M$ in 2008 and is estimated to reach up to 646 M$ by 2013. In this regard, aerogel-based thermal superinsulation has become strategically important for the 29 G$ global insulation market [23]. However, commercialization is still the most challenging point of aerogel, and hence aerogel manufacturers focus on cost reduction, performance enhancement and developing new types of aerogels [30–33]. In this paper, a thorough review of the available literature on aerogels is presented. The review is carried out in two main parts. Firstly, current scenario of the insulation market and thermal superinsulation theory is discussed. Secondly, aerogel and its applications in buildings are given in detail. Performance and economic assessment of aerogels, aerogel-based novel materials, safety and health issues, future predictions and recommendations are also considered in the study.

1.1. Heat transfer in insulation materials

Heat flow is an inevitable consequence of contact between objects of differing temperature. The function of thermal insulation is to minimize this transport of heat through the construction [34]. The heat transport in insulation materials can be divided into three parts; conduction in solid, conduction in gas phase and radiation through pores. Thermal conductivity factors by means of radiation and conduction are combined, in order to calculate the total thermal conductivity factor. In this respect, total equivalent thermal conductivity (k_{tot}) of an insulation material is given as follows:

$$k_{tot} = k_g + k_s + k_r \ (W/m\,K) \tag{1}$$

where k_g, k_s and k_r are the thermal conductivity factors for gas conduction, solid conduction and radiation, respectively. Fig. 2 shows

Nomenclature

c	specific heat capacity [J/kg K]
C	constant
Ct	thermal expansion coefficient [K^{-1}]
d	insulation thickness [m]
e	the specific extinction coefficient
g	the gravitational acceleration [m/s^2]
G	billion
Gt	gigatonne
k	thermal conductivity [W/m K]
l	free path [m]
Kn	the Knudsen number
M	million
Mt	million tonne
Nu	the Nusselt number
q	heat flux [W/m^2]
R	sound reduction index [dB]
Ra	the Rayleigh number

Subscripts

a	air
B	Boltzmann
f	fibre
g	gas
g, f	gas moving freely
hi	high
lo	low
m	mean
mod	modified
pm	porous material
r	radiation
s	solid
tot	total
w, c	with convection
wo, c	without convection

Greek letters

β	the extinction coefficient
γ	constant for the effectiveness of the energy transfer between gas molecules and solid pore
δ	the ratio of insulation material density to the fibre's material density
ρ	the insulation material's density
ν	kinematic viscosity [m^2/s]
τ	light transmittance
ω	the permeability [m^2]

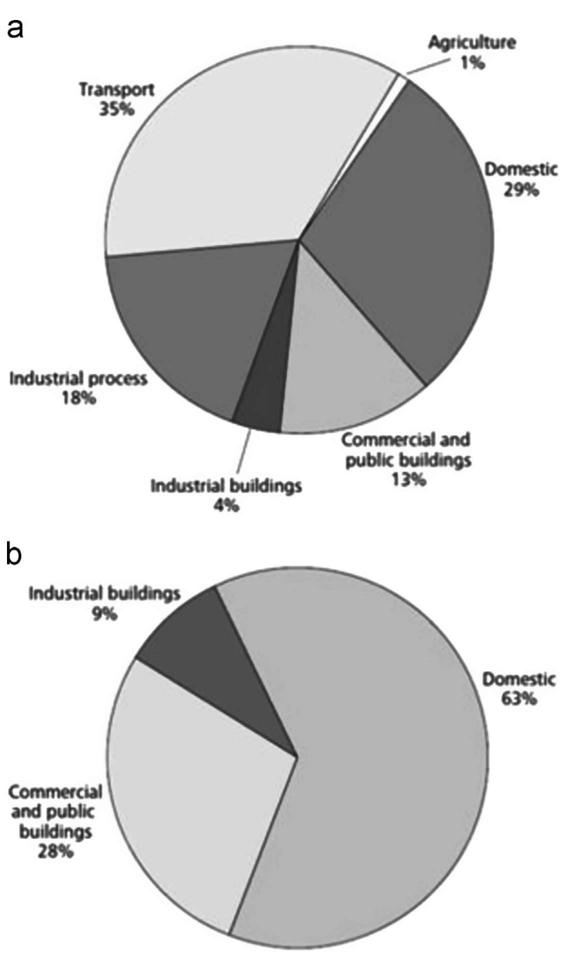

Fig. 1. Distribution of total energy consumption of United Kingdom in 2000 (a) by sector and (b) by building type [37].

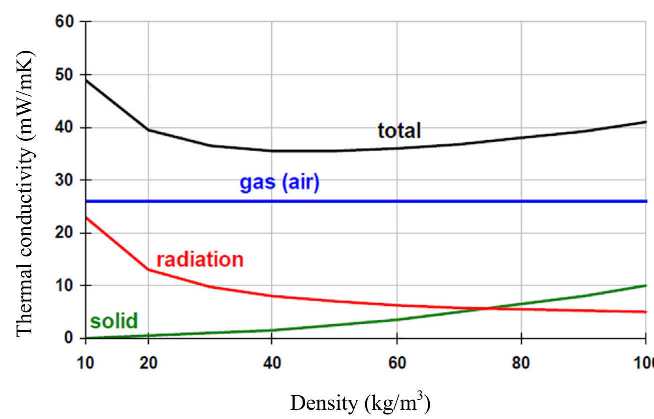

Fig. 2. Heat conductivity of conventional insulation materials [36].

the influence of conductivity factors on total equivalent thermal conductivity in porous materials. The radiation effect becomes important for the insulation materials with small amount of solid. Influence of solid conduction on the total equivalent thermal conductivity notably increases with increasing density while the importance of radiation reduces. This creates an optimum point from insulation perspective, for an insulation material, where the sum of the contributions from radiation and solid conduction is at a minimum [35,36]. On the other hand, thermal conductivity of air (≈ 0.025 W/m K) is independent of density and it leads to a minimum total thermal conductivity around 0.030 W/m K. Mineral wool, expanded polystyrene, extruded polystyrene, loose-fill cellulose and foam glass fall in this category. Heat conductivity of the aforementioned conventional insulation materials is dominated by the gas conductivity as shown in Table 1 [38]. As a result of this, scientists have a firm consensus that conventional insulation materials reached their limits in terms of performance parameters [26].

Table 1
Thermal conductivity of a number of common porous insulation materials [38].

Insulation material	k-Value (mW/m K)
Mineral wool	33–40
EPS or XPS	30–40
Loose-fill cellulose	39–42
Foam glass	39–45

Table 2
Thermal conductivity of some gases [42].

Gas	k-Value (mW/m K)
Air	25.50 (20 °C)
Nitrogen, N_2	24.10 (0 °C)
Argon, Ar	16.20 (0 °C)
R11, $CFCl_3$	8.30 (30 °C)
Carbon dioxide, CO_2	16.20 (25 °C)

1.1.1. Solid conduction

Solid conduction has a dominant impact on total equivalent thermal conductivity and it highly depends on solid material and its thermophysical properties. Therefore, an appropriate selection of the solid material is important. Density is of vital importance for solid conduction. If density decreases, the area of the solid in a cross section of the material decreases, and hence that reduces the solid conduction per square metre of the porous material. The most common equation to calculate the thermal conductivity factor through fibres is

$$k_s = k_f \delta^2 \tag{2}$$

where k_f is the fibre's material thermal conductivity factor and δ is the ratio of insulation material density to the fibre's material density. In literature, some sources combine the air's thermal conductivity factor with the fibre's one [35]. However, in this paper, they are investigated separately for a more understandable approach.

1.1.2. Radiation

Heat transfer through radiation is caused by the electromagnetic radiation that is emitted by all surfaces. Unlike conduction and convection, heat transfer by radiation can occur between two bodies, even they are separated by a medium colder than both [39,40]. The net radiation is calculated by getting the difference between the radiation from the warm surface and the radiation from the cold surface. There are several analytical methods to determine the thermal conductivity factor for radiation. The following equation considered in this study is quite simple but still leads to satisfactory results:

$$k_r = \frac{16\sigma}{3\beta} T^3 \tag{3}$$

where σ is Stefan Boltzmann constant (5.67×10^{-8} W/m^2 K^4), T is temperature and β is the extinction coefficient. The extinction coefficient is given as follows:

$$\beta = \rho e \tag{4}$$

where ρ is the insulation material's density and e is the specific extinction coefficient.

1.1.3. Gas conduction

The gas conduction theory is based on the type of gas and the possibility for the gas to transfer heat. In order to get a lower value, the gas can be exchanged to a gas with lower thermal conductivity. Alternatively, the gas can be prevented from transferring heat [34]. Examples of different gases and their thermal conductivity are illustrated in Table 2. The way of decreasing the gas conductivity is to reduce the pore size of the material. The collisions between the gas molecules and the solid are elastic which transfer small amounts of energy compared to the collisions between gas molecules. Smaller pores lead to a higher probability of collisions with pore walls instead of other gas molecules. This can be explained by the Knudsen effect which considers the gaseous conduction in a porous medium as a function of the gas pressure and the characteristic pore size [41].

$$k_g = \frac{k_{g,f}}{1 + 2\gamma Kn} \tag{5}$$

$$Kn = \frac{l_m}{\varphi} \tag{6}$$

$$l_m = \frac{C_B T}{\sqrt{2} A_{mcs} P_g} \tag{7}$$

where $k_{g,f}$ is the conductivity of the gas when moving freely, γ is a constant for the effectiveness of the energy transfer between the gas molecules and the solid pore walls with a value commonly between 1.5 and 2, Kn is the Knudsen number, l_m is the mean free path, φ is the characteristic system size, C_B is the Boltzmann constant, A_{mcs} is molecular cross-sectional area and P_g is the gas pressure. Previous works have revealed that the Knudsen effect is negligible for pores larger than 0.01 mm. In addition, it can be noted that a lower pressure gives a longer mean free path which gives a larger Knudsen effect and hence reduces the gas conductivity [34].

1.1.4. Convection in porous media

Convection in porous materials can be investigated in two categories; convection inside the pore cells and convection through the material on a macro scale. For the insulation materials with closed pore like EPS, heat transport through convection can be neglected due to negligible temperature differences on the pore cell walls. Also, micro scale convection does not occur within closed pore systems. On the other hand, for insulation materials with open cells, micro scale convection may have a significant impact on heat convection. Natural convection in porous materials is specified by the dimensionless Nusselt number which is a function of the modified Rayleigh number.

$$Ra_{mod} = \frac{\rho_a c_a g C t d \omega (T_{hi} - T_{lo})}{\nu k_{pm}} \tag{8}$$

$$Nu = \frac{q_{w,c}}{q_{wo,c}} \tag{9}$$

In the equations above, ρ_a is the density of air, c_a is the specific heat capacity of air, g is the gravitational acceleration, C_{te} is the thermal expansion coefficient, d is the thickness of the porous material, ω is the permeability factor, ν is the kinematic viscosity of air, k_{pm} is the thermal conductivity of porous material, $q_{w,c}$ is the heat flux with convection, $q_{wo,c}$ is the heat flux without convection, T_{hi} and T_{lo} are the high and low temperatures on different sides, respectively.

1.2. Prospective view of thermal insulation for buildings

The building sector is considered one of the most promising ways to be able to halt greenhouse gas emissions in the atmosphere [43]. From this point of view, a reduction of the energy consumption of buildings' HVAC systems is required to curtail CO_2 output. It can be done with minimal effort by performing thermal

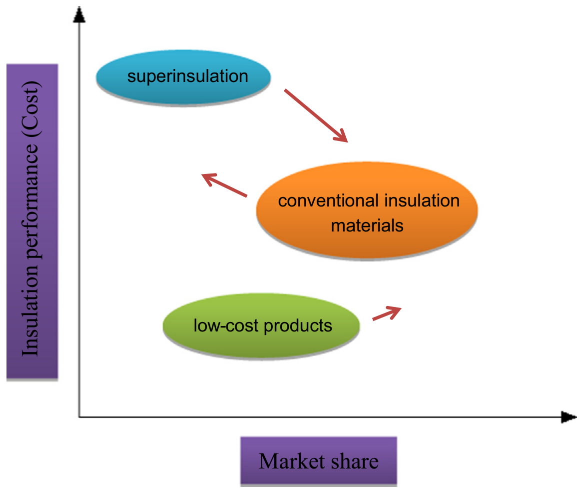

Fig. 3. A simplified view of correlation between cost, performance and market share in the insulation sector [46].

insulation but it requires installing thicker layers of conventional insulation materials. This situation causes aesthetic problems regarding the building facades. Moreover, thermal insulation with low cost products or standard materials takes up more space and decreases the volume fraction of inhabitable living space [44]. Therefore, superinsulation is compulsory to obtain the desired, attractive conditions in new constructions and retrofitting of buildings. Insulation performance and cost are the two primary parameters in thermal insulation applications of buildings. Fig. 3 depicts the comparison of three different types of insulation products with respect to the performance, cost and market share. Conventional insulation materials have the largest market potential since they offer the best performance per unit cost [45]. However, it is estimated for the near future that their cost will slightly increase and market share will reduce. Low cost products offer poor performance and durability and it is predicted that their current situation will not notably change. On the other hand, superinsulation materials like aerogels will dominate the global market in the upcoming future depending on the high performance insulation, extraordinary features and decreasing cost.

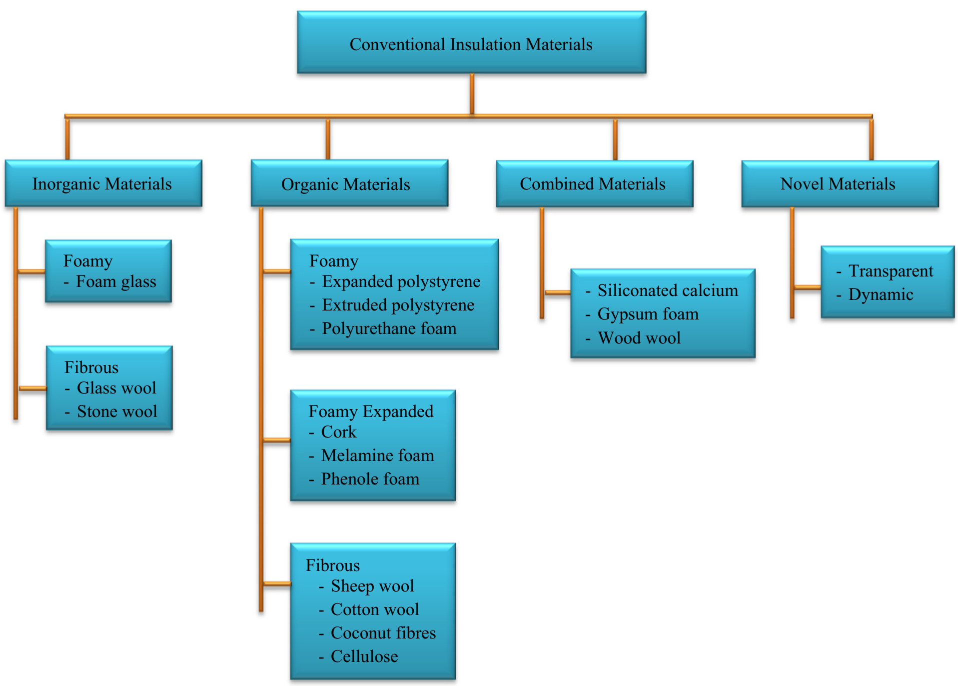

Fig. 4. A detailed classification of the conventional insulation materials.

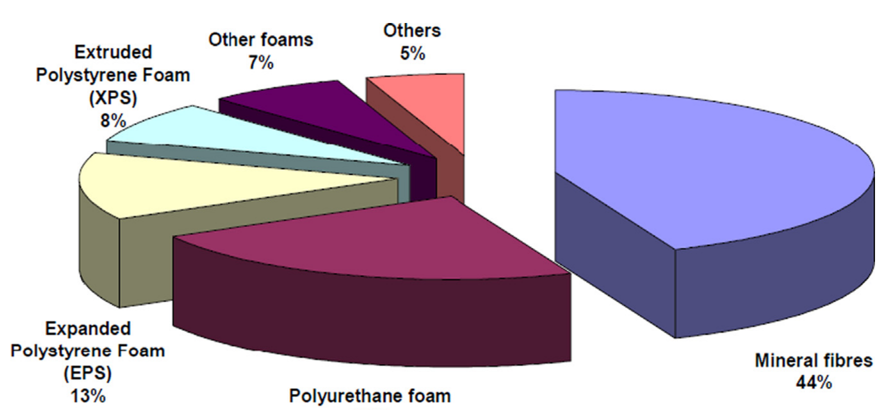

Fig. 5. Market share of the conventional insulation materials [49].

Superinsulation is quite important in terms of retrofitting old buildings since it provides space saving, advanced thermal insulation and lower servicing cost. Furthermore, it enables slim facade applications for the renovation of historical buildings.

1.2.1. Conventional thermal building insulation

As reported by Papadopoulos [47], Insulation materials can be classified according to their chemical or physical structure. Fig. 4 shows the most widely used materials of the insulation market. Especially the European market is dominated by the first two groups of products, namely inorganic fibrous materials such as glass wool and stone wool, and organic foamy materials like EPS and XPS. Currently, inorganic fibrous materials and organic foamy materials constitute 60 and 27% of the market, respectively. Conventional insulation materials have still the largest share, but the predictions for 2010–2020 indicate that they will start to lose their ascendency as a result of the developments on superinsulation materials. Cuce et al. [46] also underline that their performance per unit cost will increase depending on the remarkable reduction in manufacturing costs of thermal superinsulation materials. Today's insulation market includes a wide range of conventional insulation materials. A brief overview of them can be useful in terms of their performance assessment and potential application areas.

1.2.1.1. Mineral wool. Mineral wool is the most common conventional insulation material as illustrated in Fig. 5 and it covers glass wool and rock wool. Mineral wool was first made in 1840 in Wales by Edward Parry; however, it was first produced commercially in 1871 at the Georgsmarienhütte in Osnabrück Germany [48]. Mineral wool is generally produced as mats and boards with various densities depending on the application area. However, it may also be used as a filler material to fill cavities and spaces. Fig. 6 depicts a close-up of mineral wool. Natural or synthetic mineral resources such as rock and slag are used for mineral wool whereas recycled glass is the main material for glass wool. Rock wool is produced from melting stone at about 1500 °C, where the heated mass is hurled out from a wheel or disk and thus creating fibres [50]. In order to improve the product features of rock wool and glass wool, phenolic resin and dust abatement oil are added to bind the fibres together. The thermal conductivity of mineral wool which is normally range from 0.03 to 0.04 W/m K considerably changes with temperature, moisture and density. Mineral wool may be easily modified as cutting or drilling without losing its characteristic features.

Fig. 6. A close-up of mineral wool.

1.2.1.2. Expanded polystyrene (EPS). Expanded polystyrene has a notable market share around 13%. Expanded polystyrene consists of polymerised polystyrol (1.5–2%) and air (98–98.5%). Pentane is used as a propellant gas in the expansion process. EPS is usually white and includes small beads of polystyrene containing an expansion agent which expand by heating with water vapour [47,50]. Expanded polystyrene (EPS) is a kind of stable foam of non-absorbent, hydrophobic, closed cell nature with low density, consisting of discrete air voids in a polymer matrix [51–53]. EPS has a very wide application area. Disposable trays, plates, bowls and cups are commonly produced by EPS. In addition, it is often preferred for carry-out food packaging as seen in Fig. 7. Other uses include moulded sheets for building insulation and packing material for cushioning fragile items inside boxes [54]. EPS has a partial open pore structure and its thermal conductivity ranges between 0.03 and 0.04 W/m K. Similar to the mineral wool, the thermal conductivity of EPS varies with temperature, moisture and density. It can be easily modified as cutting or drilling without losing its characteristic features.

1.2.1.3. Extruded polystyrene (XPS). Extruded polystyrene shown in Fig. 8 is produced from melted polystyrene by adding an expansion gas mostly CO_2, HFC or C_6H_{12} and it has a closed pore

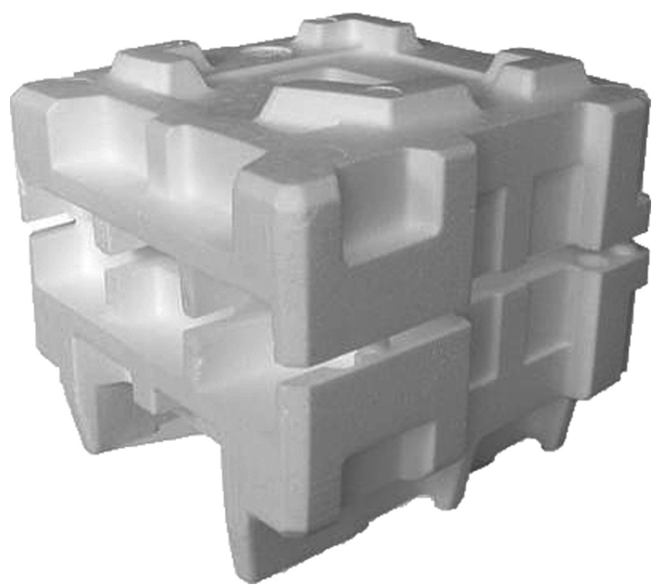

Fig. 7. Expanded polystyrene (EPS) for packaging.

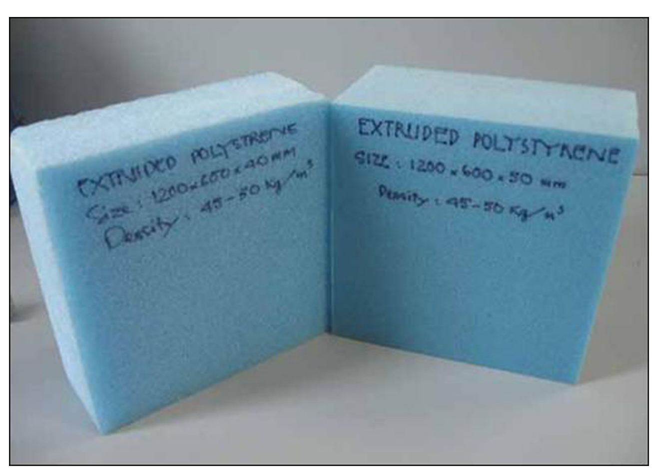

Fig. 8. Extruded polystyrene (XPS).

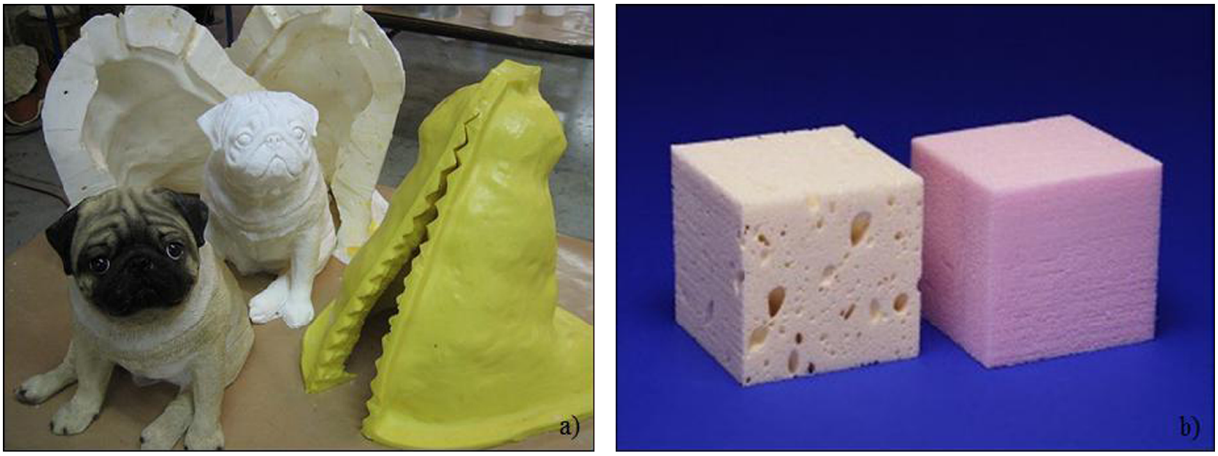

Fig. 9. (a) Polyurethane (PUR) as mould rubbers; (b) comparative shapes of PUR and XPS.

structure. The propellant gas and fire retardant additives are utilized with talcum powder and colouring elements [55]. Extruded polystyrene material is used in crafts and model building, in particular architectural models. The thermal conductivity values of XPS are usually range from 0.03 to 0.04 W/mK. However, it is highly depends on temperature, moisture and density. As reported by Jelle [50], the thermal conductivity of XPS may increase from 0.034 W/m K to 0.044 W/m K with increasing moisture content from 0 vol% to 10 vol%, respectively. XPS may be easily modified as cutting or drilling without losing its characteristic features.

1.2.1.4. Polyurethane (PUR). Polyurethane (PUR) polymers are formed by reacting an isocyanate with a polyol. Polyurethanes are used in the manufacture of flexible, high-resilience foam seating; rigid foam insulation panels; microcellular foam seals and gaskets; durable elastomeric wheels and tires; automotive suspension bushings, electrical potting compounds; high performance adhesives; surface coatings and surface sealants; synthetic fibres (e.g., Spandex); carpet underlay; hard-plastic parts (e.g., for electronic instruments); hoses and skateboard wheels. Besides those, PUR is also used to produce mould rubbers as seen in Fig. 9a. Its shape is like cheese and includes irregular cavities within material as shown in Fig. 9b. Therefore, it can be easily distinguished from the other insulation materials. PUR is manufactured as boards or continuously on a production line [56]. PUR as waste was an environmental problem but recently, a fungus has been discovered at Yale University which can digest PUR and hence help reduce plastic waste [57].

In 2007, the global consumption of PUR raw materials was calculated as 12 Mt, the annual growth rate is about 5%. Firstly R11 was used as propellant gas which was prohibited in the late 1980s and was substituted by carbon dioxide or pentane. This modification leads to an increase of the thermal conductivity of polyurethane foam [56]. The thermal conductivity values of PUR are usually range from 0.020 to 0.030 W/m K and these may be found quite lower compared to the mineral wool and polystyrene. Similar to mineral wool, EPS and XPS, the thermal conductivity of PUR varies with temperature, moisture and density. In addition it may be easily modified as cutting or drilling without losing its characteristic features.

1.2.1.5. Cork. Cork is obtained from the bark of cork tree. There is another species of cork-producing oak described by the Swiss botanist, J. Gay, in 1856. Both species are alike, and differ only in their foliage and in the ripening season of their fruits. The most

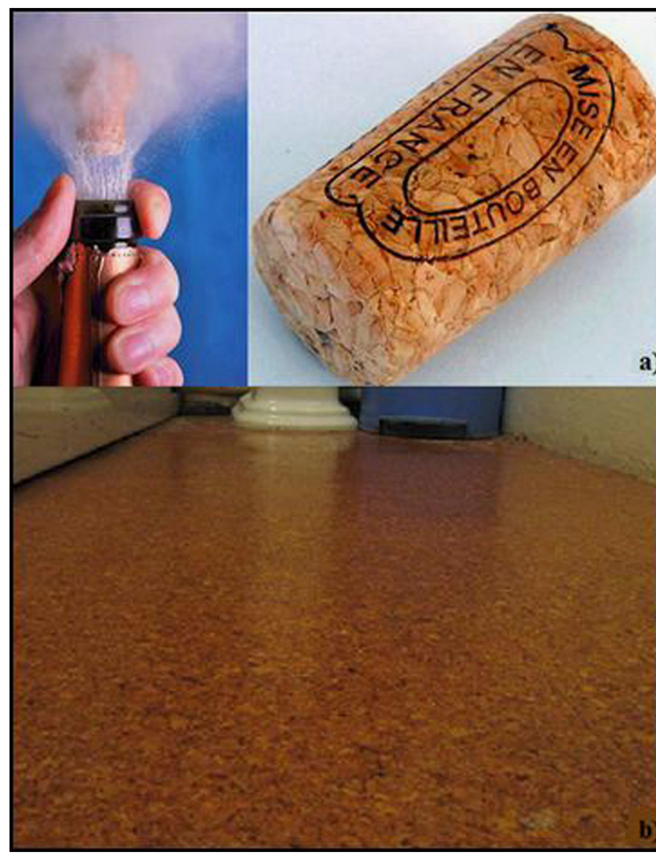

Fig. 10. (a) A cork stopper for bottles; (b) vanished cork tiles for both flooring and insulation.

important cork producer is mainly found in Portugal, Spain and North Africa. Portugal is the world's main cork supplier following Spain [63]. Cork is composed of suberin, a hydrophobic substance, and because of its impermeability, buoyancy, elasticity and fire resistance it is used in a variety of products, the most common of which is for bottle stoppers see in Fig. 10a [64]. Cork's bubble-form structure and natural fire resistance make it suitable for acoustic and thermal insulation in house walls, floors, ceilings and facades as seen in Fig. 10b. It is a suitable material for fishing floats and buoys due to its low density. Granules of cork can also be mixed into concrete. The composites made by mixing cork granules and cement have lower thermal conductivity, lower density and good energy absorption. The thermal conductivity values of cork are

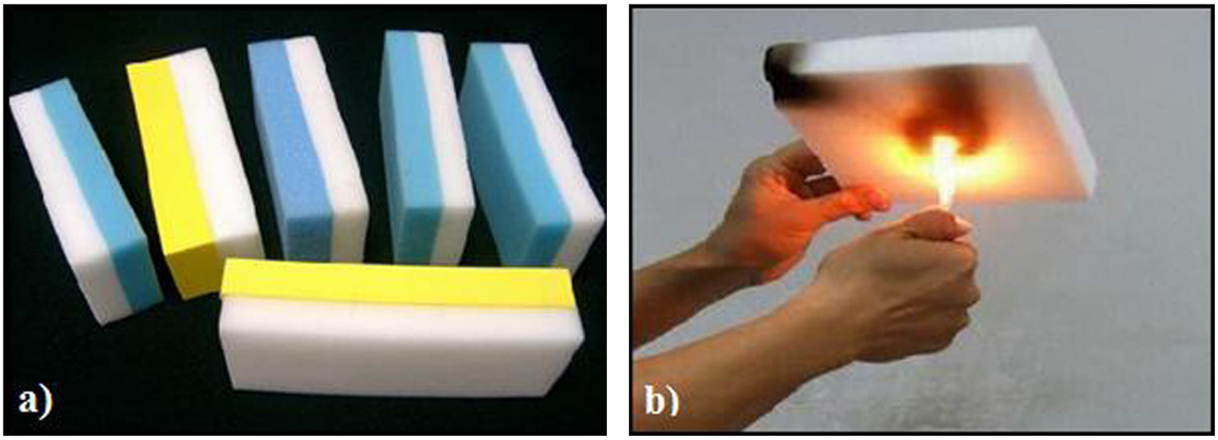

Fig. 11. (a) Melamine foam eraser; (b) melamine foam with high flame resistant.

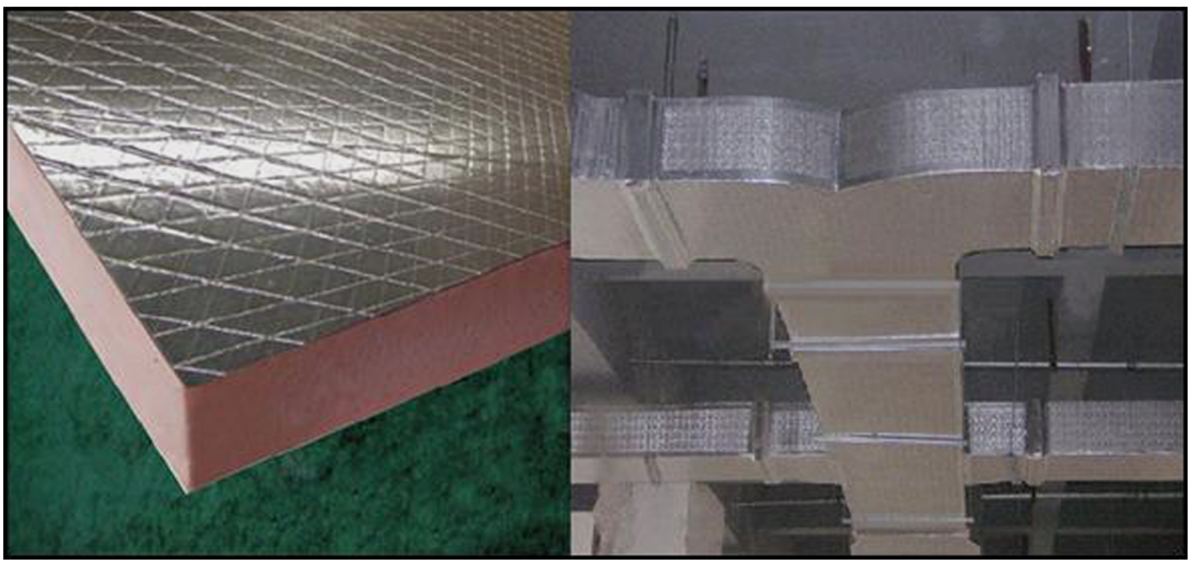

Fig. 12. Phenolic foam duct panel.

range from 40 to 50 m W/(m K) [50,64]. It may be easily modified as cutting or drilling without losing its characteristic features.

1.2.1.6. Melamine foam. Melamine foam is a foam-like insulation material. In recent years, it is commonly utilized in pipe and ductwork insulation. It also has a common use in railway carriages. Moreover, melamine foam has a long history as a soundproofing material for studios, sound stages, auditoriums, etc. [65,66]. In the early 21st century, it was discovered that melamine foam is also an effective abrasive cleaner. The open cell foam is microporous and its polymeric substance is very hard, so that when used for cleaning it works like extremely fine sandpaper. It is stated to be flame resistant to 200 °C and flame retarding, as well as thermal insulating material because of its open structure as seen in Fig. 11 [65]. Melamine foam which is lightweight, heat and flame resistant, open cell material is used for sound absorption or sound insulation in the fields of building construction and transportation. Melamine foams are also used in wedges of anechoic rooms or inside fuselages of airplanes [67]. The thermal conductivity for melamine foam is 35 mW/(m K) according to the BASF's report [65].

1.2.1.7. Phenolic foam. Phenolic foam has extremely small cell diameter and closed cell structure, and offers lower thermal conductivity than some kind of thermal insulation materials. It has been performed in heating, ventilating and air conditioning applications for over 15 years as seen in Fig. 12. Laminated phenolic board is used in roofing, cavity board, external wall board, plasterboard dry lining systems, wall insulation, floor insulation, etc. The fire performance of phenolic foam is exceptional. In recent years phenolic foams find increasing applications because of their fire retardation [68]. Phenolic foam combines zero or very low flame spread with negligible smoke emission and very low level of toxic gas emission. The phenolic foam has very low embodied energy per unit thermal performance compared to the other thermal insulation materials. It can also make a significant contribution to help achieve CO_2 emission reduction aims required by the Kyoto Protocol. In addition, it was observed in a 3 m furnace test that phenolic foam could achieve up to 2 h fire resistance rating which is used in factory engineered panels [69]. Phenolic foam has a low water vapour permeance and therefore, it is highly resistant to the passage of water vapour. The thermal conductivity value of phenolic foam is 18 mW/(m K).

1.2.1.8. Cellulose. Cellulose is an organic compound $(C_6H_{10}O_5)_n$ and it is made from recycled paper or wood fibre mass. Boric acid (H_3BO_3) and borax (sodium borates, $Na_2B_4O_7.10H_2O$ or $Na_2\ [B_4O_5(OH)_4]\cdot 8H_2O$) are added to improve the product properties of cellulose and this gives the cellulose a consistence somewhat similar to that of wool as reported by Jelle [50]. Cellulose is very appropriate as a

filler material to fill various cavities and spaces. Especially in the countries like UK, cavity wall insulation is easily performed with cellulose as shown in Fig. 13. The thermal conductivity for cellulose varies from 40 to 50 mW/(m K). Similar to the other conventional insulation materials, the thermal conductivity of cellulose varies with temperature, moisture and density. As an example, if the moisture content increases from 0 vol% to 5 vol%, the thermal conductivity of cellulose increases about 65%.

1.2.1.9. Sheep wool. Sheep wool shown in Fig. 14 has been used for hundreds of years as an insulation material. Its unique advantage is its breathability. Moisture is absorbed from the environment and released without any change in the thermal characteristics of the sheep wool. Sheep wool is natural, renewable and sustainable [70]. Although it has similar thermal conductivity range with the mineral wool, it requires less than 15% energy to produce compared to glass fibre insulation. Sheep wool has no irritating effects to the eyes, skin or lungs and wool fibres present no hazard to human health. It is hygroscopic and it can absorb up to 35% of their own weight from the surrounding atmosphere depending on the humidity, helping to preserve the surrounding timbers [70]. Sheep wool can also be used as a sound insulator. Wool fibres are commonly produced as rolls for saving time when fitting.

1.2.1.10. Other insulation materials. Besides the most common insulation materials before mentioned, there are some other insulation products such as calcium silicate and gypsum foam utilized for specific purposes. Calcium silicate (Ca_2SiO_4) shown in Fig. 15a is a white free-flowing powder derived from limestone and diatomaceous earth. It has a very low bulk density and high physical water absorption. It is generally used in roads, insulation, bricks, roof tiles, table salt and occurs in cements, where it is known as belite [71]. Calcium silicate is commonly considered as high temperature insulation. In this regard, industrial grade piping and equipment insulation is fabricated from calcium silicate. Another material that is used for fire resistance and also for sound insulation is gypsum foam shown in Fig. 15b. Gypsum foam provides a very low thermal conductivity around 20 mW/(m K). The challenging point of gypsum foam is its unsuitability for use in areas subject to continuously damp or humid conditions.

Fig. 13. Cellulose for (a) cavity wall and (b) loft insulation.

Fig. 14. Sheep wool insulation.

1.3. Global necessity of superinsulation

It is an indisputable fact that the first global oil crisis in 1970s dramatically affected the whole world and clearly showed the growing dependence of modern society on imported oil and vital need for cheap, renewable and environmentally friendly energy technologies [10,72]. Due to the limited supply of fossil fuels and growing significance of environmental issues, developed countries needed to check their energy strategies and politics. There is also a crucial need stabilize the CO_2 concentration in the atmosphere and minimize its effects on the global climate [5–7]. Caldeira et al. [8] pointed to stabilization of atmospheric CO_2 concentration below 500 ppm as a first step. That was a significant move but very difficult to implement in a short period because of the huge dependence on oil, gas and coal. Moreover, replacing fossil fuel based applications with renewable energy technologies all over the world included some technological difficulties and economic barriers [73]. Nevertheless, short term, medium term and long term strategies were developed to narrow the gap between fossil fuels and renewable energy systems. Aegerter et al. [44] presented appropriate strategies for halting global climate change sorted by time and source. The target steps were

divided into three groups called mobility, power plants/heavy industry and buildings as illustrated in Table 3. The results surprisingly indicated that building sector play a remarkable role on global energy consumption, a larger share than that of the mobility sector. It was also noted that HVAC (heating, ventilation and air conditioning) has the lion's share of buildings' energy consumption. This situation provided a necessity of higher thermal insulation standards which can be named as superinsulation.

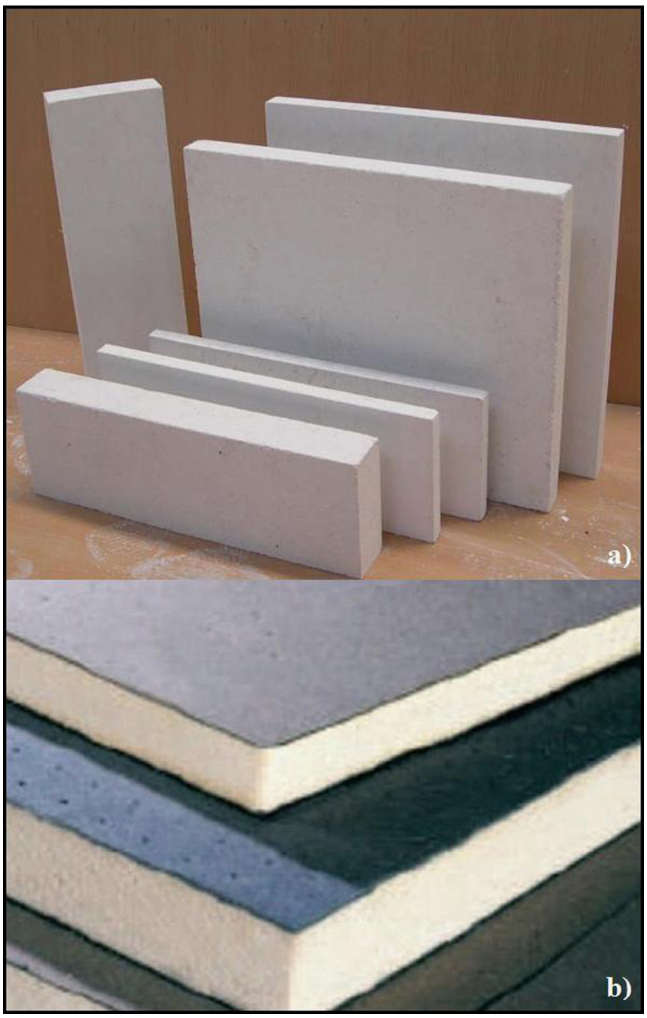

Fig. 15. (a) calcium silicate and (b) gypsum foam.

1.4. Theory of superinsulation

Superinsulation or high-performance insulation is a term which is used for materials with thermal conductivity lower than 0.020 W/m K. It is well-known in physics that thermal conductivity (λ) is an intrinsic property of a materials' ability to conduct heat [74]. Metals are known very good conductors and their λ values range from tens to hundreds of W/mK. Glass, sand and minerals have single digit thermal conductivities. Common thermal insulation materials such as glass wool, rock wool, expanded polystyrene and extruded polystyrene have λ values in the range of 0.03–0.04 W/m K. High performance foam insulation materials such as polyurethane and phenolic resins are considered as transition materials between conventional and superinsulation materials [44]. Table 4 illustrates an overview of insulation materials with respect to their thermal conductivity range. It can be clearly seen that aerogels, vacuum insulation panels and vacuum glazing offer extremely low thermal conductivities which enable to call them as superinsulation materials.

Among the superinsulation materials, aerogel stands out with its extraordinary features and rapidly developing market share. Aerogel was first found by Samuel Stephens Kistler in 1931 [27,28] and ever since that time it has rapidly developed. Especially in recent years, studies have focused on cost reduction and developing new types of aerogels. In this review, both thermophysical properties and various applications of aerogels in buildings are investigated in detail. Space saving effect of aerogels in buildings is analysed in a comparison with conventional thermal insulation materials. Possible health problems by aerogels and suggestions to avoid them are also considered in the study.

2. Aerogels

The term “aerogel” comes from the fact that they are manufactured from gels. In contrast with their name, aerogels are rigid, dry materials and do not resemble a gel in their physical properties. They also have an extremely high porosity [74,75] and translucent structure. Fig. 16 depicts the resistant structure and outstanding insulation feature of aerogels. Aerogels have considerably high specific surface area, quite low apparent density and low refraction index. Apparent (bulk) density is defined as the mass of many particles of the material divided by the total volume they occupy. The volume includes particle volume, inter-particle void volume and internal pore volume [76].

2.1. Synthesis

Synthesis of aerogels consists of three steps: preparation of the gel, ageing the gel and drying the gel. Dorcheh and Abbasi [77]

Table 3
Short, medium and long term strategies for halting global climate change [44].

Short-term	Medium-term	Long-term
Mobility		
Increasing drive efficiency, hybrid systems, weight reduction	Only electrical and hybrid vehicles, car prototypes are available on markets	Short range mobility powered fuel cell and hydrogen technology picks up, fossil fuels for long range mobility
Power plants/Heavy industry		
Establishing possibilities for CO_2 sequestering, slight increase in nuclear plants to cut peaks	Sequestration implemented growing contributions of renewables (sun, wind, water), improved electrical storage	All plants operate nearly CO_2 free, renewables dominate the mix, nuclear and fossil fuelled plants are only support, robust grid and storage systems are in place
Buildings		
Reducing energy demand of HVAC by thermal insulation, developing zero energy buildings	New buildings are CO_2 neutral, wide use of photovoltaics, retrofitting of old buildings required by laws	$>50\%$ Of all buildings are no net producer of CO_2, retrofitting of all buildings continues, buildings store notable amount of electricity

Table 4
Overview of thermal insulation materials sorted by their thermal conductivity range [44].

Insulation product	Chemical composition	λ (W/m K)
Mineral wool	Inorganic oxides	0.034–0.045
Glass wool	Silicon dioxide	0.031–0.043
Foam glass	Silicon dioxide	0.038–0.050
Expanded polystyrene (EPS)	Polymer foam	0.029–0.055
Extruded polystyrene (XPS)	Polymer foam	0.029–0.048
Phenolic resin foam	Polymer foam	0.021–0.025
Polyurethane foam	Polymer foam	0.020–0.029
Silica aerogels	SiO_2 based aerogel	0.012–0.020
Organic aerogels	Aerogels derived from organic compounds	0.012–0.020
Vacuum insulation panels (VIP)	Silica core sealed and evacuated in laminate foil	0.003–0.011
Vacuum glazing (VG)	Double glazing unit with evacuated space and pillars	0.003–0.008

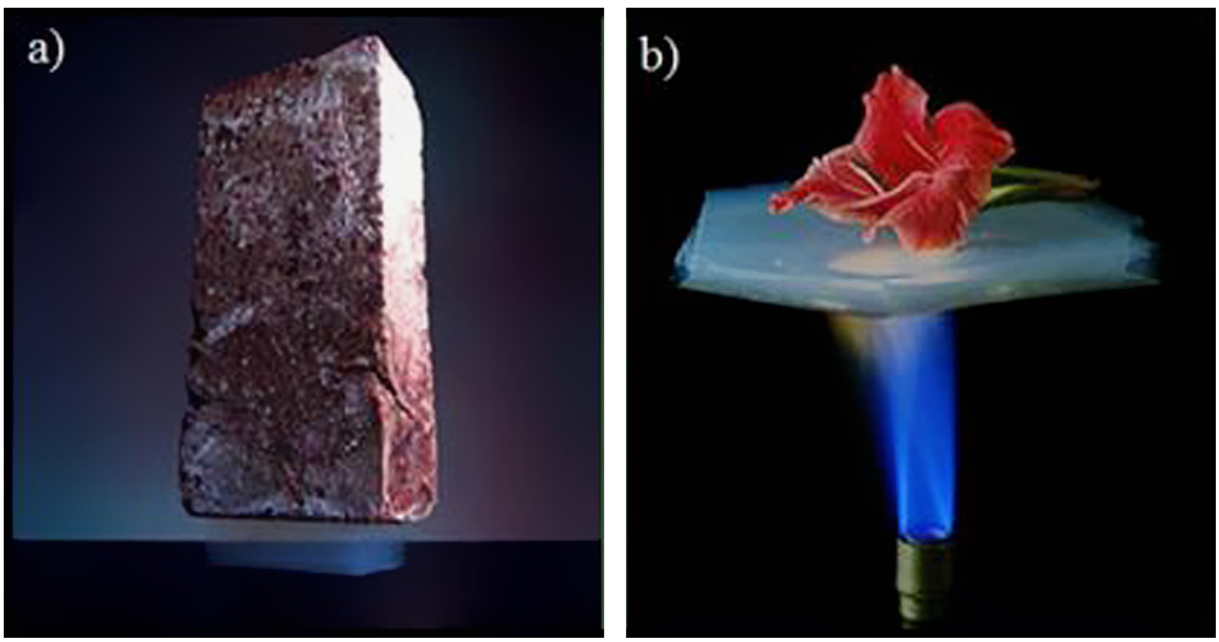

Fig. 16. (a) Aerogel with a mass of only 2 g supports a 2.5 kg brick; (b) flower is protected from the flame via the superior insulating property of aerogel.

have presented a comprehensive review on the synthesis of silica aerogels. In gel preparation process, solid nanoparticles are dispersed in a liquid agglomerate to form a continuous three-dimensional network throughout the liquid. This process was described in detail by Brinker and Scherer [78]. After the gel is prepared, it is aged in its mother solution in order to prevent the gel from shrinking during drying. Common ageing procedures include ethanol–siloxane mixtures. After ageing the gel, all water still within the pores must be removed before drying, which can be performed by washing the gel with ethanol and heptane [79]. Otherwise, that will cause an opaque and very dense aerogel. After the ageing process, the gel is dried. Drying is the final stage and generally two different methods are used for drying the aerogels: ambient pressure drying (APD) and supercritical drying (SCD). In APD, capillary tension cannot be avoided. On the other hand, this problem can be overcome in SCD above the critical temperature and pressure. There are two different applications of SCD: high temperature supercritical drying (HTSCD) and low temperature supercritical drying (LTSCD). HTSCD was explained by Kistler [80] and LTSCD was presented by Tewari et al. [81]. APD is the most cost effective way compared to HTSCD and LTSCD. In this method, drying is carried out via ambient pressure evaporation.

2.1.1. Gel preparation

In materials science, the sol–gel process is known as a method in order to produce solid materials from small molecules. The method is utilized for the fabrication of metal oxides, especially the oxides of silicon and titanium. The process covers conversion of monomers into a colloidal solution (sol) that acts as the precursor for an integrated network (or gel) of either discrete particles or network polymers [82]. Aerogels are basically the solid framework of such a gel isolated from its liquid medium [23]. The main precursors for silica aerogels are silicon alkoxides. $Si(OCH_3)_4$ (tetramethoxysilane), $Si(OC_2H_5)_4$ (tetraethoxysilane) and $SiO_n(OC_2H_5)_{4-2n}$ (polyethoxydisiloxane) are the most frequently used, where polyethoxydisiloxane can be obtained by reacting tetraethoxysilane with a substoichiometric quantity of water in an acidic alcoholic medium according to:

$$Si(OC_2H_5)_4 + nH_2O \leftrightarrow SiO_n(OC_2H_5)_{4-2n} + 2nC_2H_5OH \tag{10}$$

for n lower than 2 [83–85]. In terms of thermal conductivity range, tetramethoxysilane and polyethoxydisiloxane have notably lower thermal conductivity compared to the tetraethoxysilane aerogel monoliths. On the other hand, tetraethoxysilane is the most appropriate one for the production of high quality transparent

aerogels [86,87]. Hydrolysis of silicon alkoxides is carried out with a catalyst which is usually acid catalysis or a two-step catalysis [88]. The sol becomes a gel when the solid nanoparticles distributed into it stick together to form a medium of particles spanning the liquid as reported by Baetens et al. [23]. Acid hydrolysis and condensation essentially results in linear or weakly branched chains and microporous structures in silica sols [89] and the resulting gelation times are generally long. On the opposite, uniform particles are easily formed in base catalysis and leads to a broader distribution of larger pores, which is less favourable for thermal insulation materials [90].

2.1.2. Aging

After a sol reaches the gel point, the silica spine of the gel still includes a great number of unreacted alkoxide group. Hydrolysis and condensation may continue and sufficient time must be provided for the strengthening of the silica network, improved by controlling the pH, concentration and water content of the covering solution [91,92]. Two different mechanism can affect the structure of the gel during ageing: transport of material to the neck region and dissolution of small particles into larger ones. Common ageing procedures typically cover ethanol–siloxane mixtures [79], thus adding new monomers to the solid SiO network and rising the degree of cross-linking. The gel should be washed by ethanol and heptane after ageing in order to remove the remaining water from the pores. Any water left in the gel causes an opaque and very dense aerogel as underlined by Baetens et al. [23].

2.1.3. Drying

Drying is vital of importance in aerogel production. There are two most common drying processes called ambient pressure drying and supercritical drying. In ambient pressure drying capillary tension cannot be prevented. On the other hand, this can be achieved by removing pore liquid above critical temperature and pressure.

2.1.3.1. Supercritical drying. Supercritical drying is the first and most common method for the drying process of aerogels. In supercritical drying, gels are dried at a critical point to elucidate the capillary forces. During the evaporation of the liquid from the gel, concave menisci is created by surface tension in the pores of the gel [93]. Effect of the compressive forces around the pore increases with time, and the tension causes the collapse of the gel body [94]. In order to prevent gel from the surface tension, the gel is exposed to supercritical drying in an autoclave as illustrated in Fig. 17. As increasing the temperature and pressure in the autoclave above a critical point, the liquid is transformed into a supercritical fluid where each molecule is able to move freely and the surface tension is removed. Any menisci cannot form without surface tension. Then, the fluid is isothermally depressurized until the pressure of the autoclave reaches atmospheric pressure. Methanol is the most frequently used solvent for supercritical drying of aerogels [95]. Supercritical drying can be split into two categories as high temperature and low temperature supercritical drying. High temperature supercritical drying has been found the most appropriate method to minimize the shrinkage of the gel [96].

2.1.3.2. Ambient pressure drying. Supercritical drying is the most common method for drying gels, however it has certain limitations such as cost efficiency, process continuity and safety. In addition, the chemical durability of aerogels remarkably decreases when liquid CO_2 is used as a solvent in the low temperature supercritical drying. Brinker [78] developed and introduced a commercially attractive drying process called ambient pressure drying for the production of silica aerogels. As reported by Gurav et al. [93], in this method, the surface of the wet gel is chemically modified by substituting hydrophobic functional groups by replacement of H from hydroxyl groups. Finally, drying is performed by ambient pressure evaporation [78]. In recent years, ambient pressure drying is most interest due to its very low production costs.

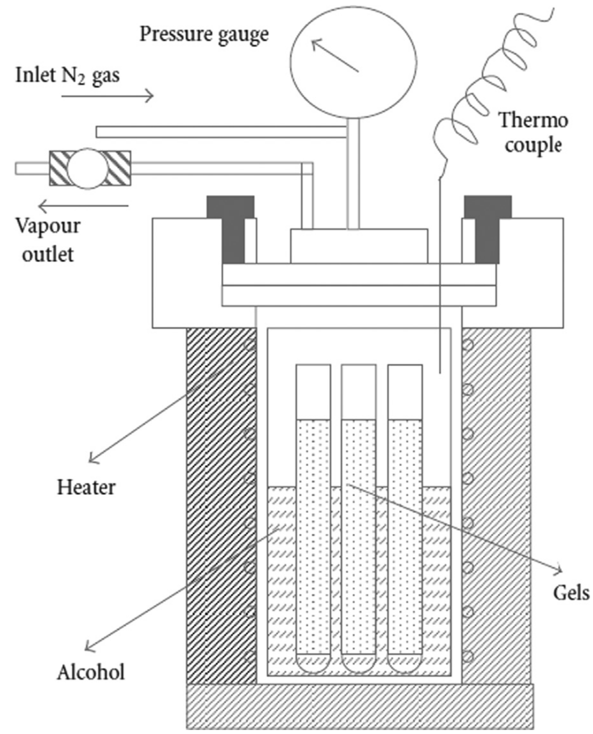

Fig. 17. Supercritical drying of aerogel in an autoclave [93].

2.1.3.3. Freeze drying. Freeze drying is another option for the drying process of aerogels. In this method, the pore liquid is frozen and then sublimed in vacuum [97–99]. One of the challenging points of this method is the long aging period to be able to stabilize the gel network. Also, the solvent must be replaced by one with lower expansion coefficient and higher sublimation pressure.

2.2. Characteristic features of aerogels

There are three types of aerogels called silica, carbon and alumina aerogels. Among the three types, silica aerogel is the most common; the most extensively investigated and used type. Silica aerogels have some outstanding solid properties. They consist of a cross-linked internal structure of SiO_2 chains with a large number of air-filled pores [23]. These pores of aerogels are quite small. Diameter of the pure aerogel and silica aerogel varies from 10 to 100 nm and 5 to 70 nm, respectively [100]. Aerogels have extremely low bulk density of about 3 kg/m^3 owing to the high porosity structure. However, aerogels with an overall density of 100 kg/m^3 are preferred for the building applications. Specific surface area of aerogels varies from 600 to 1000 m^2/kg. Aerogel as a super insulating glazing has an overall heat transfer coefficient below 0.5 W/m^2 K [101]. One of the challenging points of aerogels is being fragile due to their low tensile strength. Other physical properties of aerogel are illustrated in Table 5 [102,103].

2.3. Detailed comparison of aerogels with other thermal insulation materials

Before comparing the characteristic properties of aerogels with other conventional insulation materials, some simple definitions might be useful to make the key items more comprehensible. Thermal insulation can be defined as a material or combination of materials,

Table 5
Physical properties of silica aerogels [102,103].

Property	Value	Property	Value
Density (kg/m^3)	3–350 (Most common $\approx$ 100)	Primary particle diameter (nm)	2–5
Pore diameter (nm)	1–100 ($\approx$ 20 On average)	Surface area (m^2/g)	600–1000
Porosity (%)	85–99.9 (Typical $\approx$ 95)	Index of refraction	1.0–1.05
Thermal conductivity (W/m K)	0.01–0.02	Thermal tolerance temperature (°C)	500 (Melting point 1200)
Transmittance in 0.5–2.5 μm, 3.7–5.9 μm	0.80–0.95	Coefficient of linear expansion (1/°C)	$2.0–4.0 \times 10^{-6}$
Longitudinal sound speed (m/s)	100–300	Tensile strength (kPa)	16

that, when properly applied, retard the rate of heat flow by conduction, convection and radiation [104]. It resists heat transfer into or out of a building as a result of its high thermal resistance [104,105]. Thermal resistance is a measure of the opposition of heat flow due to the suppressing heat transfer mechanisms. It is a function of material thermal conductivity, thickness and density as reported by Al-Homoud [104] and it is expressed in m^2K/W. Thermal conductance is the rate of heat flow through a unit surface area of a material with temperature difference between the surfaces of the two sides of the material.

Thermal insulation materials retard heat flow as a result of the micro-scale air cells provided inside the material. These microscopic gaps filled with immobile air provide a high thermal resistance and notable reduces heat losses. However, air-based insulation materials are not able to exceed the thermal resistance value of still air. Therefore, high performance thermal insulation or superinsulation materials are required for applications where minimizing the heat losses is crucial. There are many advantageous for using thermal insulation in buildings. First of all, great energy savings can be obtained via thermal insulation. Greenhouse gas emissions can be minimized. Indoor thermal comfort conditions are kept for long periods especially between seasons. Disturbing noise sources from neighbouring spaces or from outside can be avoided. Vapour condensation on building surfaces can be prevented.

There are many types of thermal insulation but they can be classified into three main groups: inorganic materials, organic materials and metallic or metallized membranes. Inorganic materials consist of fibrous materials such as glass, rock and slag wool, and cellular materials like calcium silicate, bonded perlite, vermiculite and ceramic products. Similarly, organic materials involve fibrous materials such as cellulose, cotton, wood or synthetic fibres and cellular materials like cork, foamed rubber, polystyrene, polyethylene, polyurethane and other polymers. Insulation materials are also used in different forms like mineral fibre blankets, rigid boards, insulated concrete blocks, insulated concrete form etc. depending on the application area [104].

Apart from the conventional insulation materials mentioned above, aerogels provide high performance thermal insulation as a result of their extremely low thermal conductivity. It stands out as a good opportunity for retrofitting old buildings or restoration of historical places. It is mostly possible to construct slim facades with aerogel insulation due to its notably low density. Aerogel is also a perfect sound insulator and fire retardation material which makes it extraordinary among the alternative insulation materials. Table 6 depicts a detailed comparison of aerogel with conventional insulation materials.

2.4. Applications of aerogels

Outstanding properties of aerogels enable them to be used as building components for various purposes. The unique low thermal conductivity and optical transparency of aerogels allow its applications in roofs, window panes and solar collector covers [102]. Acoustic properties of aerogels make them a good sound insulator. In addition, dimensional stability and high performance thermal insulating feature make possible to be utilized in building facades and envelopes. Moreover, aerogel is a non-combustible material due to its non-organic structure. It withstands heat up to 1200 °C (its melting point). Therefore, it also can be used inside buildings as fire-retarding construction. In recent years, some aerogel products like *Pristina* have been utilized for removal of indoor air contaminants and clean-up of outdoor environment [106].

2.4.1. Building applications of aerogels

Aerogel has a wide range of applications in buildings. The most common examples stand out at roofs, facades and windows [21]. In addition to those applications, aerogel is preferred for several purposes such as sound insulation, fire retardation and air purification. Superior space saving effect of aerogel also enables it to be used in the restoration and reconstruction of historical buildings such as museums and art galleries.

2.4.1.1. Aerogel applications in roofs, facades and windows. Silica aerogels are seen as one of the most promising insulation materials for building applications although their cost still remain high compared to the conventional insulating materials. However, intensive efforts are going on to reduce their manufacturing cost and develop novel types of aerogels. Through the literature, it can be easily said that aerogel applications in buildings for daylighting goals become widespread. Two examples of translucent aerogel insulation as a high performance thermal insulation solution for daylighting purposes are illustrated in Fig. 18 [23,107]. Another application is conducted on Yale University Sculpture Building and Gallery as shown in Fig. 19 [108]. Retrofitting of an old brick dwelling with Aspen aerogel is illustrated in Fig. 20a. Difference between an insulated and non-insulated facade in a dwelling is illustrated in Fig. 20b. The facade is monitored with a thermal camera and as it is clear there is a considerable amount of heat loss is occurred from the ground floor. On the contrary, the top floor which is insulated with aerogel seems an efficient barrier to the heat loss [30]. Kaushika and Sumathy [109] have prepared a review about solar transparent insulation materials. Transparent insulation materials have been shown to increase the efficiency of solar thermal conversion systems. They offer good possibilities of their applications where the typical working temperatures were between 50 and 80 °C. However there were many solar thermal processes with higher working temperatures in the range of 80–120 °C; these include desalination and cooling processes absorption and absorption cycles [109]. Wong et al. presented a review of transparent insulation systems and the evaluation of payback period for building applications. They suggested that transparent insulation materials not only performed similar functions to opaque insulation, reducing heat losses and controlling indoor temperatures but also allowed solar transmittance of more than 50%. With a thickness of less than 20 cm, it could provide a financial return to building occupants when applied to building facades without compromising thermal comfort within buildings. Current cost information relating to transparent insulation systems was inadequate and their payback period was not available. The simple payback time calculations indicated that payback period of the aerogel insulation material ranged 5–8 year for a discount rate of 10% [110].

Table 6
Aerogel in a comparison with other thermal insulation materials [102].

Form	Material	Density[a] [kg/m^3]	Thermal conductivity [W/mK]	Fire resistance	Effect as vapour barrier [%]	Effect as infiltration barrier	Resistance to direct sunlight	Max. service temperature [°C]	Durability	Sound absorption [%]	Cost per *R*-value	Potential health risks	Typical applications
Blankets: batts or rolls	Fibreglass (sand and recycled glass)	12–56	0.44–0.033	Good	Poor fair (with facing)	Poor fair (with facing)	Excellent	−4–260	Compression reduces *R*-value	High	Low	Inorganic (organic binders), Irritating dust during installation	Frame wall or ceiling, partitions, prefabricated houses, irregularly shaped surfaces, ducts and pipes. Settling is expected
	Rockwool (natural rocks)	40–200	0.037	Excellent	Poor	Poor fair (with facing)	Excellent	−240–800	Compression reduces *R*-value	V. high	Low	Inorganic (organic binders), Irritating dust during installation	Frame wall or ceiling partitions, prefabricated houses, irregularly shaped surfaces, ducts and pipes. Settling is expected
	Polyethylene	35–40	0.041	Poor	Good	Good	Good	−40–90	*R*-value decreases w/time		Low	Organic (off-gassing, toxic smoke)	Ceiling, hangers, wrapping, carpet underlay, expansion joints
Loose-fill blown-in or poured-in	Fibreglass (open cell structure)	10–48	0.038–0.030	V. good	Poor (1% of weight)	Poor	Excellent	−4–260	Comp. & moisture degrade *R*-value	High	Low	Inorganic (organic binders), Irritating dust during installation	Cavities and around obstructions. Added adhesive provides more resistance to infiltration
	Rock wool (open cell structure)		0.040	Excellent	Poor (1% of weight)	Poor	Excellent	−240–800	Comp. & moisture degrade *R*-value	V. high	Low	Inorganic (organic binders), Irritating dust during installation	Cavities
	Cellulose (ground-up waste paper)	24–36	0.054–0.046	V. good (added fire Resisting chemicals)	Poor (5% to 20% of weight)	Poor	Good	80	Comp. & moisture degrade *R*- value	Low	Low	Organic. Irritating dust during installation	Blown into small cavities
	Perlite (natural glassy volcanic rock)	32–176	0.06–0.04	Excellent	Fair	Good	Good	760	Good	Low	High	Inorganic	Fill or mixed with Portland cement for walls, roofs and floors, plastering
	Vermiculite	64–130	0.068–0.063	Excellent	Poor (dries slowly)	Good	Good	1315	Good	Low	High	Inorganic	Poured into ceilings, cavity walls and cores of hollow core blocks
Rigid boards	Fibreglass (open cell Structure)	24–112	0.035–0.032	Good	Good (0.2%)	Good	Excellent	−4–350	More rigid than batts	Medium	Medium	Inorganic (organic bonds)	Cavity walls, roofs and prefabricated structures
	Expanded Polystyrene (closed cell foam)	16–35	0.038–0.037	Poor	Good (1.0–2.5%)	Good	Poor	100	*R*-value decreases w/time	Low	Lowest of rigid board Types	Organic (uses pentane gas as the expanding agent, toxic)	Walls, roofs and floors. Must be covered inside for fire and against for fire and against outside weather
	Extruded Polystyrene (closed cell foam)	26–45	0.032–0.030	Poor	Excellent (0.2–1.0%)	V. good	Poor	100	*R*-value decreases w/time	Low	High	Organic (uses HCFC or CFC gases as the expanding agent, toxic fumes)	Walls, roofs, floors, perimeter, basements and foundations. Must be covered inside for fire and against outside weather

	Polyurethane & Polyisocyanurate (closed cell foam)	40–55	0.023	Poor	Good (0.5–1.5%)	Excellent	Poor	95	*R*-value decreases w/time	Low	High	Organic (uses CFC or CO_2 gases as the expanding Agent, toxic fumes)	Walls and roofs. Must be covered inside for fire and against outside weather
	Perlite (natural glassy volcanic rock)	32–176	0.06–0.04	Excellent	Fair	Excellent	Good	760	High	Low	High	Inorganic	Blocks (industrial/commercial insulation), light weight concrete
	Vermiculite (natural mineral)	64–130	0.068–0.063	Excellent	Good	Excellent	Good	1315	V. high	Low	High	Inorganic	Not in houses (heavy weight)
Sprayed-in-place	Cellulose (waste paper)	24–36	0.054–0.046	V. good (added adhesives)	Poor	V. good	Good	80	fire retardant chemical may corrode metals	Low	High	Organic. Requires protection against inhaling fine particles	Attics retrofitting, wood frame sidewalls (experienced help needed). Needs time to dry before enclosing to avoid moisture problems
Foamed-in-place	Polyurethane & Polyisocyanurate (closed cell foam)	40–55	0.023	Poor	Good	Excellent	Poor	95	XXXX	Low	High	Organic (toxic smoke, off-gassing from aging plastics)	Roofs, cavities, irregular and rough surfaces (experienced help needed). Hard to control quality and thickness on site. Needs time to dry before enclosing to avoid moisture problems
Reflective systems	Aluminized thin sheets (reflective foil, separated by airspaces)[b]		Reduces only radiant heat transfer[c]	Good	Excellent	Excellent	Excellent	High	[d]				Ceilings, walls and floors. Most effective in reducing downward heat flow (i.e., summer heat gain in cooling dominated climates, usually installed directly under the roof). Fabricated in a variety of packing includes kraft paper, plastic film, polyethylene bubbles
	Ceramic Coatings (acrylic paint filled with ceramic micro spheres-brush, roller or spray)	1.25	Radiation control	V. good	Excellent (seamless water proofing)	Excellent	Excellent	High	High (rust proofing)			Requires protective clothing and eye protection when applied	Metal roofs, built-up roofing, walls, storage systems. Ducts and pipes
Translucent solid	**Aerogel**	**3–100**	**0.012–0.020**	**Excellent**	**Excellent**	**Good**	**Excellent**	**High**	**Excellent**	**Excellent**	**High**	**Requires protective clothing and eye protection when applied**	**Buildings**, **spacecrafts**, **automobiles**, **electronic devices**, **clothing etc**.

[a] Thermal conductivity varies with material density and thickness as well as temperature and moisture content.
[b] If one single reflective surface is used facing an open space, it is called Radiant Barrier.
[c] The effectiveness of resistance to heat flow depend on spacing, airspace orientation and heat flow direction. Must have low emittance (≤ 0.1) and high reflectance (≥ 0.9).
[d] Foil must face air space with face down to prevent dust accumulation.

Fig. 18. Aerogel applications over large areas in new buildings [23,107].

Fig. 19. A facade application of aerogels at the Yale University Sculpture Building and Gallery [108].

Schultz et al. [111] carried out an EU project on super insulating glazing based on monolithic silica aerogel. Prototypes measuring roughly $55 \times 55\ cm^2$ have been made with 15 mm evacuated aerogel between two layers of low-iron glass. Thus anti-reflective treatment of the glass and a heat-treatment of the aerogel increased visible quality and solar energy transmittance. A centre heat loss coefficient of the prototypes was found below 0.7 $W/m^2\ K$ and solar transmittance of 76%. A granular aerogel based window was developed by ZAE Bayern (Germany) [112–114]. Granular silica aerogels was integrated into highly-insulating translucent glazing. To avoid settlement of the granules, which often occurred in earlier glazing concepts and even caused destruction of the glazing, the granules were sandwiched between a double skin sheet made of polymethyl-methacrylate (PMMA). The sheet was mounted between two low-e-coated glass panes. To optimize the thermal insulation, krypton was used as filling gas. This construction allowed achieving heat transfer coefficients of less than 0.4 $W/m^2\ K$. Optimised granular layers provided high solar transmittance of 65% for thicknesses of 20 mm. Reim et al. [114] used two types of granular aerogel in prototype windows. They are semi-translucent spheres with a solar transmittance $T_{sol} = 0.53$ for a 10 mm packed bed and highly-translucent granules with a $T_{sol} = 0.88$. The aerogel glazing has already been integrated into facades and has turned out to be a visually

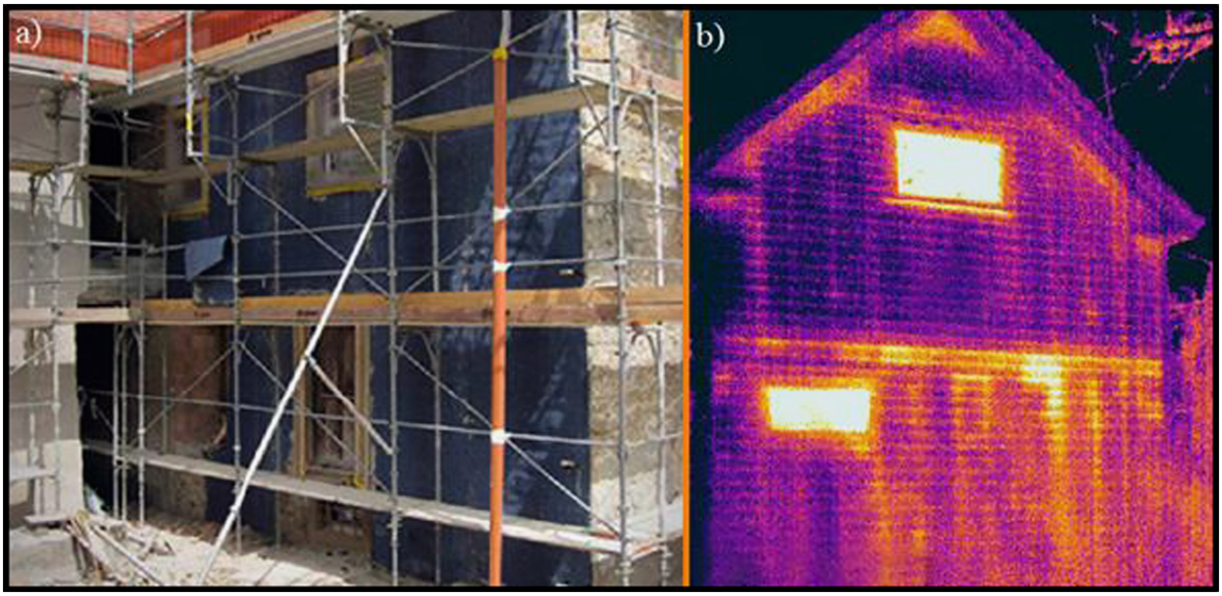

Fig. 20. (a) Retrofitting of an old brick dwelling with Aspen aerogel; (b) difference between an insulated and non-insulated facade in a dwelling [23].

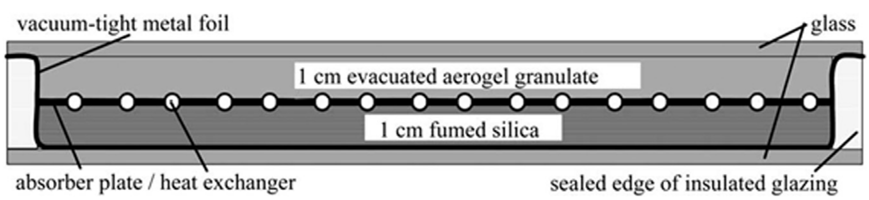

Fig. 21. Cross-section view of an evacuated solar collector filled with aerogel granules [114].

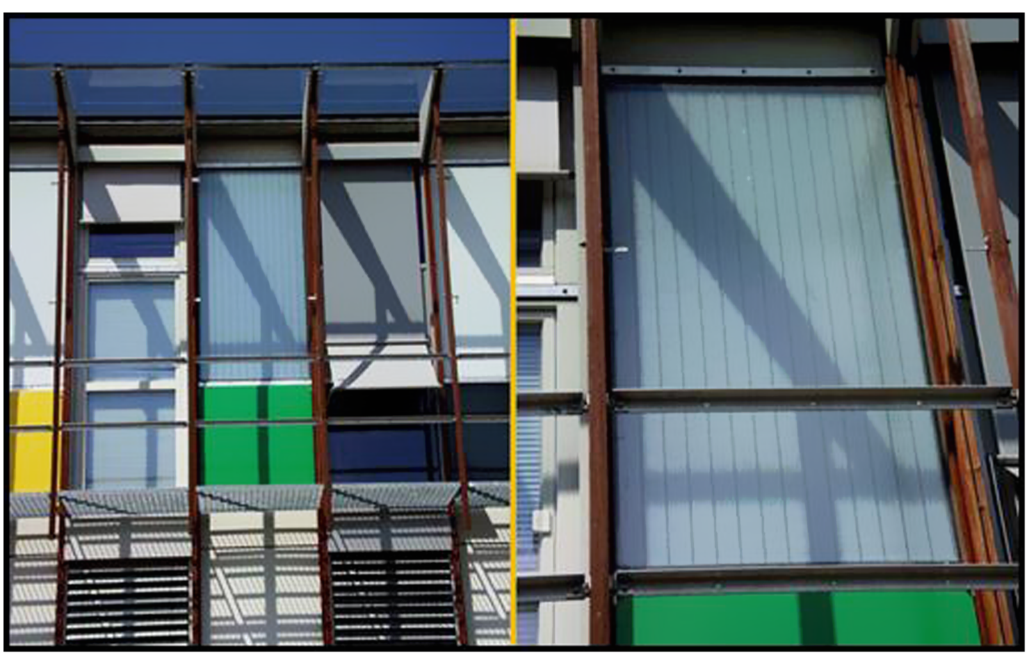

Fig. 22. Aerogel glazing integrated in the facade of the ZAE building in Wurzburg [114].

attractive, light-scattering daylight element with extremely low energy loss during the heating period. Evacuated solar collector augmented with aerogel granules, integration of the collector in the facade of the ZAE building in Wurzburg and aerogel glazing window are illustrated in Figs. 21, 22 and 23, respectively.

Jensen et al. [115] carried out an EU project and developed a monolithic aerogel-based window. This window was developed in combination with the technology of vacuum glazing by applying a pressure between 1 and 10 mbar. An overall heat loss coefficient U_{window}=0.66 W/m^2 K and a T_{sol} of more than 0.85 were measured

for an evacuated glazing with 13.5 mm thick aerogel, while the noise reduction of the glazing was measured 33 dB [23]. The results of the study showed that an energy saving of 1180 kWh/year (19%) by exchanging triple-layered argon-filled glazing with aerogel glazing in a typical new built single family house in climate conditions of Denmark [116]. An aerogel ambient drying process was developed by Kim and Hyun [117] in order to synthesize window glazing coated with silica aerogel films. The silica aerogel films were synthesis at a temperature of 270 °C and a pressure 1 atm. Thus the transmittance of window glazing was over 90% which is more than 12% higher than that of an uncoated glass slide. The thermal conductivity of aerogel-window glazing decreased as aerogel film thickness increased. Duer and Svendsen [101] examined a number of different aerogels for their optical and thermal performance. High thermal resistance of aerogel was found for all the investigated samples and the samples showed very high solar as well as light transmittance. However all of the samples tended to scatter the transmitted light, resulting in a reduced optical quality when the aerogels were integrated in glazing.

Integration of aerogel into glazing systems started to appear on the market in 2005 [116,118]. At the University of Perugia, Buratti and Moretti [119–123] carried out several experimental works on aerogel glazing systems. The main goal of their works is to investigate the optical and thermal properties of advanced glazing systems with aerogel in order to evaluate their possible employing in buildings for energy savings. They analysed both monolithic and granular aerogel glazings as illustrated in Fig. 24. The most promising of the investigated materials is found to be the monolithic aerogel, because of the better light transmittance (τ=0.62) together with very low U-values (about 0.60 W/m^2 K in a double glazing with evacuated conditions), lower thickness (14 mm) and high lightness. On the other hand, for the granular systems the light reduction is about 60% if compared to a double glazing with a low-e layer; the U-value is little higher than 1 W/m^2 K with the same total thickness [120]. The results also indicated that the monolithic aerogel innovative glazing systems allow to obtain thin windows with U-values lower than 0.5 W/m^2 K, without diminishing the solar factor or reducing considerably the daylight transmittance. In another work, Buratti and Moretti [119] compared the thermal and acoustic performances of a conventional window (double glazing with a low-e layer) and a monolithic aerogel window. It is observed from the results that 55% reduction in heat losses is achieved by monolithic aerogel in comparison with the conventional window. On the other hand, not a notable enhancement in acoustic properties was found as shown in Fig. 25. In order to improve further the acoustic performance of the window, the authors recommended integrating granular aerogel into laminated glasses with special acoustic PVB (polyvinyl butyral) layer. Wu et al. [127] performed a feasibility analysis of five types of aerogel glazings in five climate zones of China (Harbin, Beijing, Shanghai, Guangzhou and Kunming). The results indicated that the construction 5 (4 mm clear glass outer + 15 mm aerogel interlayer + 4 mm clear glass inner) has the best thermal characteristics among the configurations evaluated. Heat transfer coefficient and shading coefficient of the best case were determined to be 0.72 W/m^2 K and 0.59, respectively.

2.4.1.2. Aerogels for sound insulation, fire retardation and air purification. The dispersion bound aerogel plate shows a notably improved sound insulation [124]. Buratti and Moretti [119] manufactured eight samples by assembling several types of glass with monolithic and granular aerogel in the interspace. It was found that the monolithic aerogel was a better light transmittance (τ = 0.60) than granular one (τ = 0.27). They stressed that the granular aerogel in interspace could improve sound insulation of the building envelope. The acoustic measurement also showed that the weighted sound insulation index R for the aerogel window prototype was 3 dB higher than the same window with air in interspace. Gibiat et al. [125] investigated acoustic properties of cylindrical silica aerogels in both ultrasonic and audible range. Velocity measurements for low ultrasonic frequencies showed that the low-density aerogels could exhibit unexpected attenuation for well-defined frequency bands. However measurements of the acoustical impedance of samples in the audible range showed that the results depended dramatically on the geometry and/or the boundary conditions imposed to the samples.

Many pollutants are released into the indoor environment, including chloride from tap water, hydrocarbons (CH_3CHO and CH_3CHOH)

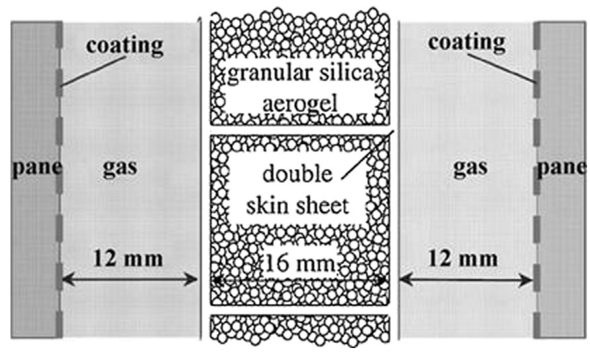

Fig. 23. Cross-section through the aerogel-glazing consisting of two glass panes [114].

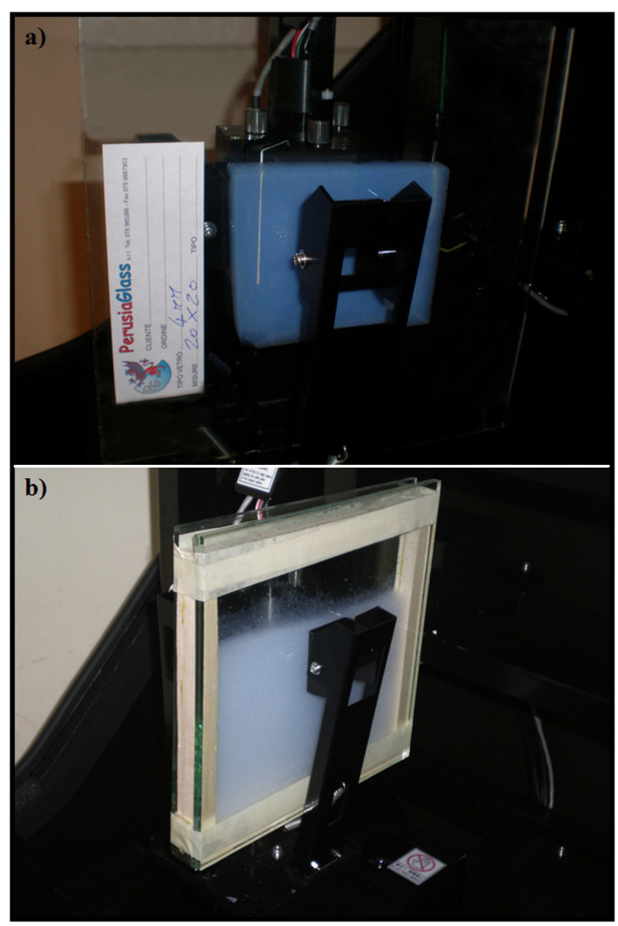

Fig. 24. (a) Monolithic aerogel and (b) granular aerogel glazings [120].

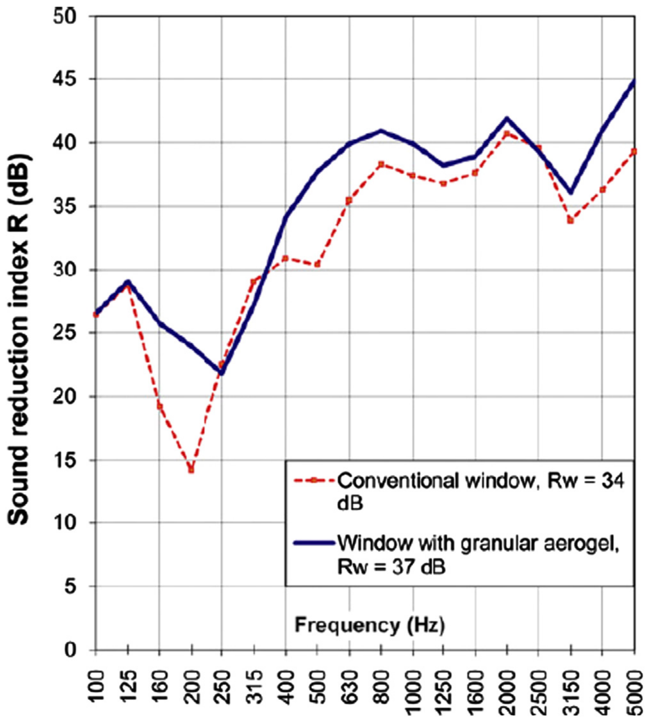

Fig. 25. Sound reduction index (R) values vs. frequency for the conventional window and for the glazing prototype with aerogel in interspace [119].

from cigarettes, formalin from furniture and paints, NO_x and SO_x from the incomplete burning of gas and VOC from organic solvents. Some allergies and respiratory problems, such as asthma, are exacerbated by airborne contaminants and their conversion into non-toxic compounds is an effective route for their removal [102,126]. Aerogels are capable of selective and efficient removal of many pollutants/contaminants from air as reported by TAASI [106]. Aerogels have extremely high melting point (1200 °C) and they are non-flammable due to their chemical structure. Therefore they are used inside buildings to avoid spreading of fire from one place to another.

2.4.1.3. Benefits of using aerogel in old buildings. Aerogels provide many opportunities for retrofitting old buildings and renovating historical places. In recent years, Aspen Aerogels Company has developed a high performance thermal insulation material called *Spaceloft* for building envelopes [128]. Spaceloft improves energy efficiency while conserving space and maintaining building's characteristic features. It is used externally and internally on the walls and also internally on the floors. In external applications, traditional rendering systems are conducted with a standard metal mesh to protect the system. On the other hand, in internal applications, standard plaster is used to allow a breathable solution that let entrapped vapour "breathe" through the wall [128]. *Spaceloft* provides extremely low overall heat transfer coefficient for facades ranging from 1 to 0.2 W/m^2 K. Installation is quite easy and does not require professional skills. After installation, building sustains its characteristic properties. Aerogels have translucent structure hence they can be used between window panes and on roofs for both daylighting and insulating purposes. Although they are fragile, they have excellent dimensional stability and serves superior thermal insulation in facades with slim and light constructions. Restoration of historical places, museums etc. requires using insulation materials with fire retardation property as well as low thermal conductivity and density. Aerogels are non-combustible so they may be seen a good choice to protect those kind of special buildings from unexpected catastrophes. Aerogels can be applied without the need for major changes to the building structures such as windows, doors, roofs and facades.

2.4.1.4. Space saving effect of aerogels. Besides all its superior characteristic features, aerogel has a space saving effect which enables to construct slim facades and roofs in buildings. Conventional insulation materials have remarkably higher thermal conductivity range than aerogels. Therefore, it is required to use thicker forms of them in order to meet the standards of sustainable homes. As an instance, for the referenced standard, overall heat transfer coefficient (U) and the thickness of the walls should be 0.11 W/m^2 K and 440 mm, respectively [129]. If the prescribed wall is insulated with aerogel, volume fraction of inhabitable living space increases about 67% which is quite higher than conventional insulation materials as illustrated in Table 7. Moreover, aerogels are as light as air and hence do not cause extra weight to building construction. On the contrary, conventional insulation materials have extremely high density range which makes them weaker against aerogel. Space saving is a crucial point in buildings and from this point of view; aerogel is regarded as one of the most appropriate insulation material especially retrofitting and renovating applications.

2.4.1.5. Research at the University of Nottingham. Energy-efficient retrofitting of residential buildings is a concept which is extensively investigated at the University of Nottingham through research projects (HERB – Holistic energy-efficient retrofitting of residential buildings. European Union Project, Project No: 314283, 2012; Eon Retrofit Research House Phase 3.1, 2012; A high performance vacuum tube window. Project CALEBRE, 2013). As one of the objectives of the research, a test house was constructed at the University Park Campus and one of the bedrooms of the test house was internally insulated with 20 mm aerogel blanket. Co-heating test procedure was performed to the test bedroom before and after retrofitting, and thermal characteristics were determined both theoretically and experimentally. Thermal bridging effects were also analysed with thermal imaging data at pre and post-retrofit. Test house, test bedroom, and the places insulated with aerogel are illustrated in Fig. 26. In the pre-retrofit case, the external wall of the house consisted of gypsum plaster, 13 mm, k=0.40 W/m K; concrete block, 100 mm, k=0.45 W/m K; cavity fill, 50 mm, k=0.04 W/m K and brickwork, 102 mm, k=0.77 W/m K from inside to outside. The theoretical U-value of the existing external wall was 0.55 W/m^2 K. Then, 20 mm of aerogel was applied and 12 mm of gypsum plasterboard was implemented internally on the aforementioned parts of the test bedroom. The U-value of the external wall after post-retrofit was determined to be 0.30 W/m^2 K which results in reduction of heat losses around 46%. Aerogel provides slimmer constructions with superior thermal characteristics. It also has a remarkable impact on

Table 7
Space saving effect of aerogels in comparison with conventional insulation materials.

	U (W/m^2 K)	δ (mm)	Space saving (%)
Level 6 zero-carbon house	0.11	440	–
Conventional insulation materials	0.11	309	29.7
Aerogel	0.11	145	67.1

Fig. 26. Test house, test bedroom and internal wall insulation of aerogel (blue-colored). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

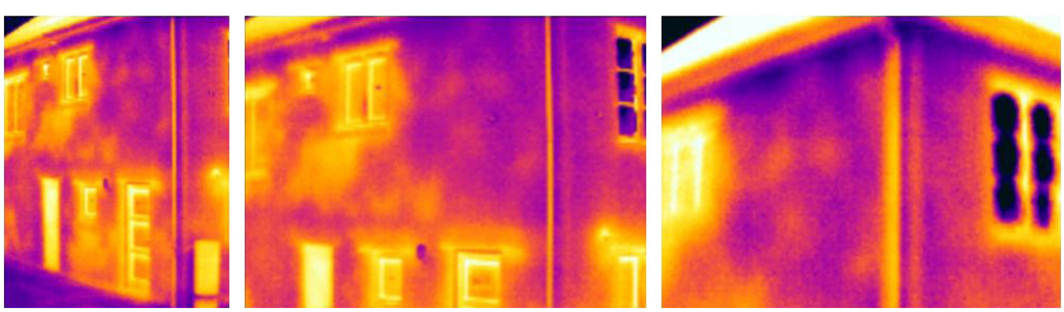

Fig. 27. Effect of aerogel insulation on heat loss through the external wall of the test house.

minimizing thermal bridging in buildings. This can be concluded from the thermal imaging data of post-retrofit case as shown in Fig. 27.

2.5. Performance assessment of aerogels

Silica aerogels are the most common type in the market due to their unusual solid material properties. As a consequence of its superior small pore sizes and high porosity, the aerogel achieves its extraordinary physical, thermal, optical and acoustical properties, whereas this also results in a very low mechanical strength. The characteristic high porosity makes aerogels the lightest solid material known at the moment. Its skeleton density is about 2200 kg/m^3, but the high porosity can result in a bulk density as low as 3 kg/m^3 [130]. Existing aerogels for building applications have an average density of 70–150 kg/m^3 as reported by Baetens et al. [23]. Performance assessment of aerogels can be done as thermal, visual and cost performance.

2.5.1. Thermal performance

As a consequence of low solid skeleton conductivity, low gaseous conductivity and low radiative infrared transmission, aerogel has a very low thermal conductivity at the moment ($\approx$0.01 W/mK) which makes it special among the other thermal insulation materials [131]. Depending on its extraordinary thermal properties, numerous researches have been made in recent years for further enhancements of its performance. Biesmans et al. [132] investigated the feasibility of making polyisocyanurates (PIR) and polyurethanes (PUR) based aerogels in the density range from 80 to 400 kg/m^3. Effects of different physical forms and different densities of aerogels on thermal performance were analysed as a

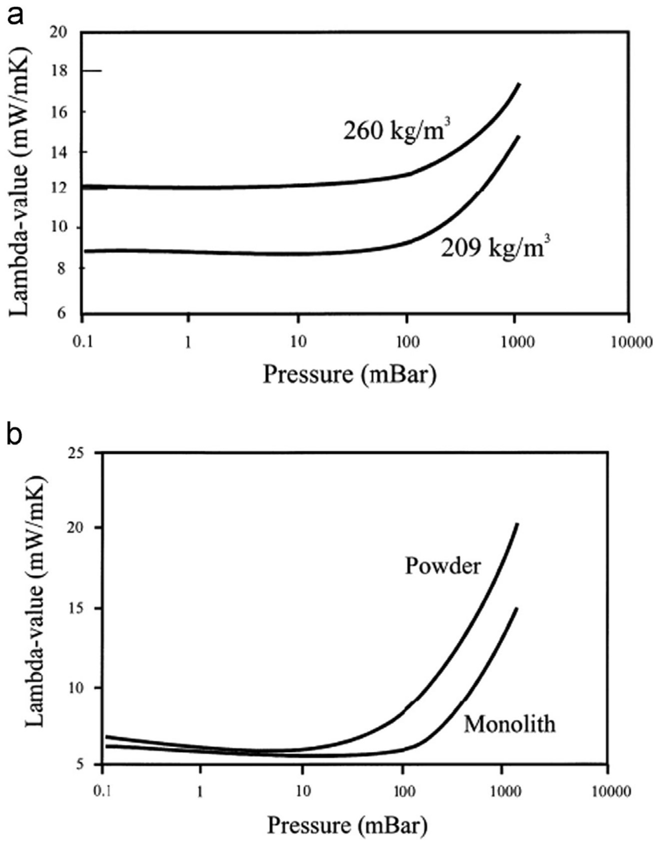

Fig. 28. (a) Thermal performance of aerogel monoliths of different density as a function of pressure; (b) thermal performance of PIR aerogels as a function pressure for different physical forms.

function of pressure as shown in Fig. 28. The results showed that it is possible to produce samples with a thermal performance of 7 mW/m K below 10 mbar pressure and an air filled value of 22 mW/m K for an aerogel pack with a density of 150 kg/m^3. Lee et al. [133] measured the thermal conductivity values of polyurea based aerogel at pressures from ambient to 0.075 torr and at temperatures from room temperature to -120 °C under a pressure of 8 torr. The polyurea based aerogel samples demonstrated high porosities, low thermal conductivity values, hydrophobicity properties, relatively high thermal decomposition temperature (≈ 270 °C) and low degassing property and were less dusty than silica aerogels. The low thermal conductivity of polyurea based aerogels was a consequence of their small pore sizes. Fig. 29 depicts the temperature dependency of thermal conductivity of polyurea based aerogels under a pressure of 8 torr. It is understood from the results that the aerogels serve superior thermal performance at low operating temperatures.

2.5.2. Visual performance

Optical properties of aerogels have been widely studied by researchers in recent years in order to understand the feasibility of its use in glazing systems [134–137]. Silica aerogels have high transmittance of radiation within the range of visible light which can be seen from Fig. 30. As previously reported by Reim at al. [113], monolith translucent silica aerogel in a 10 mm thick packed bed has a solar transmittance of 0.88, and it is possible to improve this value with optimal synthesis parameters. In their experimental work, Buratti and Moretti [120] compared the direct and the total transmittance of the aerogel pane sample and found that aerogel has very interesting optical properties for building applications and its transmittance is high in the whole solar spectrum, including the visible part. This result was found to be similar to the conventional clear float glass of 6 mm thickness as illustrated in Figs. 31 and 32. In another work, Buratti and Moretti [119] analysed the visual performances of different aerogel glazing samples. The result indicated that Xtralite glazing systems show a 50% reduction in transmission when the thickness of granular aerogel increases from 16 to 25 mm. The transmission of the Okagel sample is quite low and it is approximately 0.1 in the visible range. Schultz and Jensen [116] investigated the main characteristics of monolithic silica aerogel and its application in evacuated superinsulating aerogel glazings. It was observed that the scattering is dominant if the aerogel glazing is exposed to direct sunlight. Strong diffusion of the sunlight made the glazing almost impossible to look through. Therefore, it was concluded that aerogel is more suitable for north facing windows.

2.5.3. Cost performance

Low cost products and conventional insulation materials still predominate in the insulation market as a consequence of their

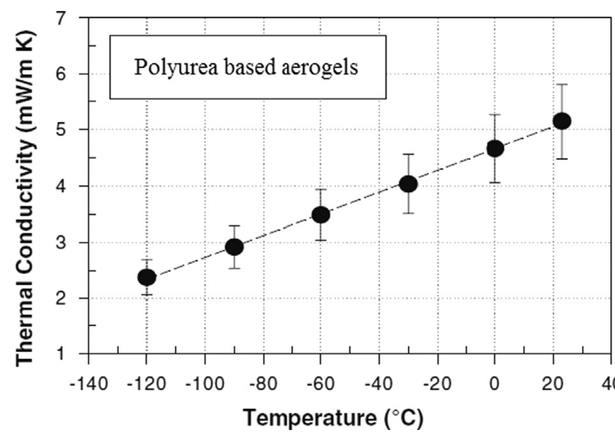

Fig. 29. Temperature dependency of thermal performance of polyuria-based aerogels.

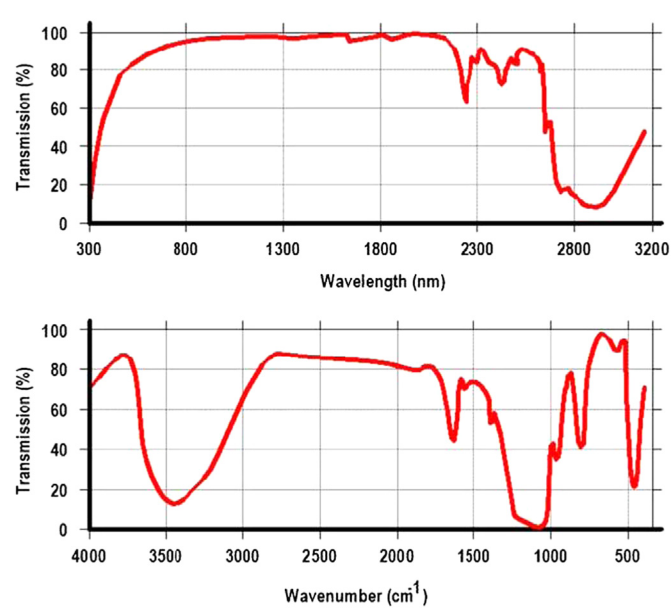

Fig. 30. The transmittance of a silica aerogel in the ultraviolet, visible and near infrared spectrum (top) and the infrared spectrum (bottom) [23].

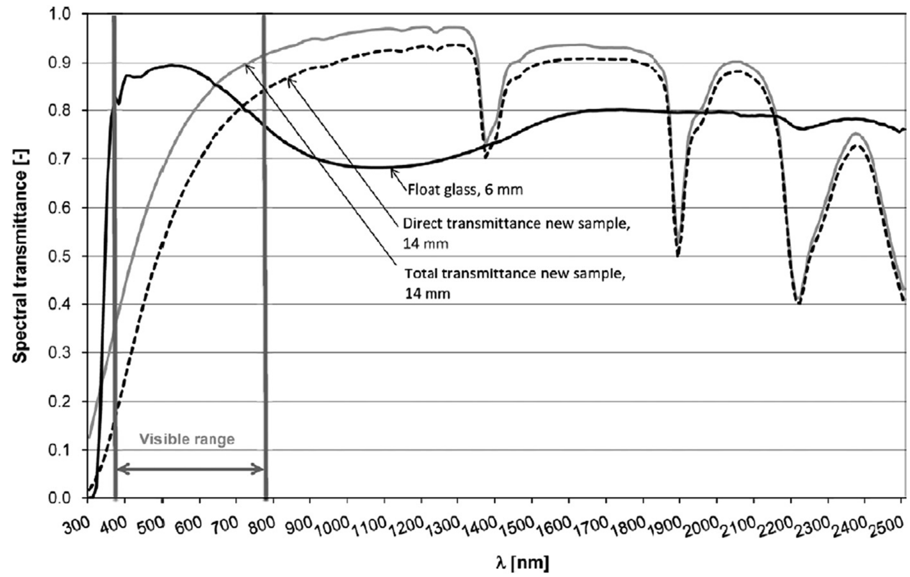

Fig. 31. Aerogel pane transmission optical properties: direct and total solar spectral transmittance in comparison with a 6 mm thickness float glass [120].

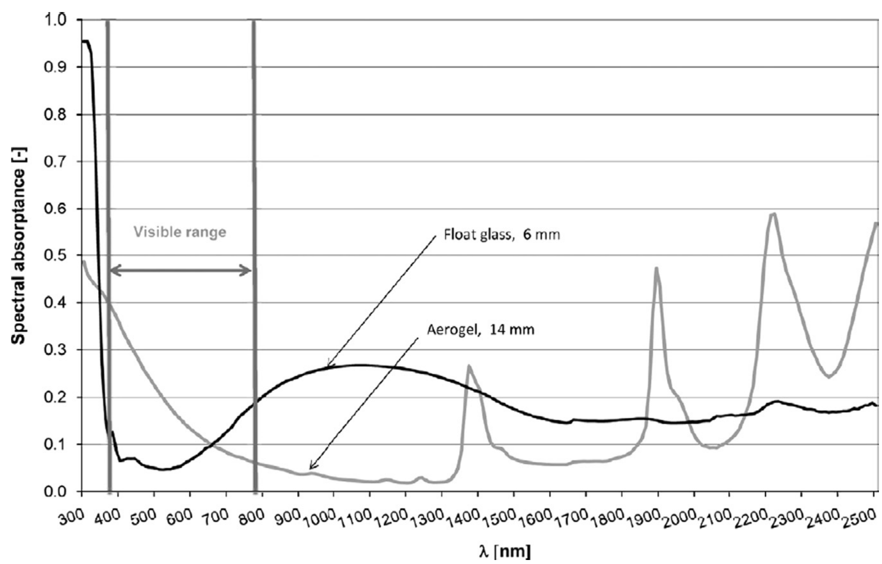

Fig. 32. Spectral absorptance of aerogel pane compared to conventional a 6 mm thickness float glass [120].

reasonable cost. With respect to the current scenario presented by Koebel et al. [4], there is a huge gap between conventional and superinsulation materials in terms of cost as shown in Fig. 33, however future predictions notify that the unit m^3 cost of aerogel will be reduced below £500 by 2050, which can make the aerogel first in the market as a result of its superior thermal, visual and acoustic performance [138]. Another point raised by Koebel et al. [4] is the importance of "space saving effect". They emphasize that in order for a high priced superinsulation material such as aerogel to become competitive with conventional ones, the value of the space saving and other beneficial factors must compensate remarkably for the added cost of the material.

In order to provide context to the cost performance of aerogel, life cycle cost analysis must be performed for the purpose of comparisons against alternative conventional insulation materials. For this review paper, a simple life cycle cost situation has been considered, but of course the number of permutations relating to current and future scenarios are abound. The life cycle cost analysis has been carried out for a typical solid brick wall (the thickness is 225 mm, *U*-value is 2.3 W/m^2 K), which would be typical for a UK property built in the early 20th Century. The results have been compared with a common conventional insulation material (glass wool). In this respect, the insulation thicknesses of the materials have been firstly determined to be able to achieve a *U*-value of 0.3 W/m^2 K, which corresponds to the typical wall *U*-value for modern housing in the UK. A degree day-based methodology [149,150] has been used in the analyses, and the value of degree day has been taken to be 2549 through the weather data of Nottingham, UK. The life time of the investment has been considered as 10 years. The interest and the inflation rates have been taken as 3.5% and 2%, respectively for the UK, with an investment life time of 10 years. The results have indicated that the insulation thickness of glass wool to obtain the objective *U*-value is 104 mm, whereas it is only 37 mm for the aerogel. When the heating energy is chosen as electricity at £0.15/kWh and an aerogel cost of £500/m^3 is applied the payback period of aerogel insulation has been determined to be about 1 year, which is also very competitive compared to the glass wool.

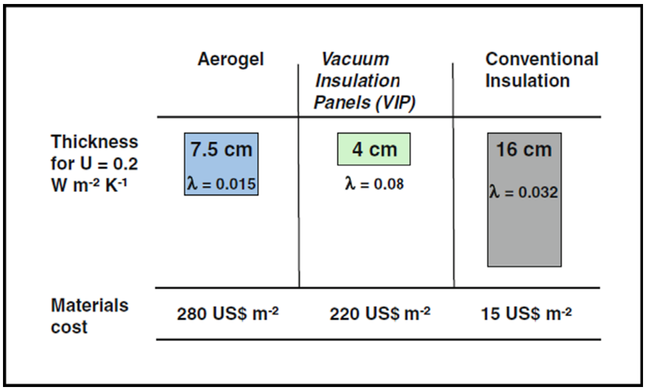

Fig. 33. Comparison of space savings and cost of conventional insulation and superinsulation [4].

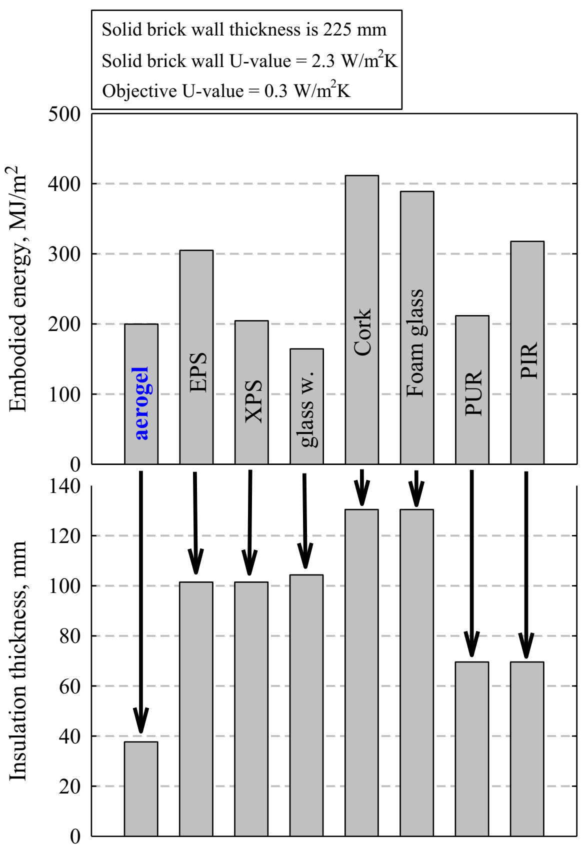

Fig. 34. Comparison of embodied energy and insulation thickness values for aerogel and other conventional insulation materials.

2.5.4. Embodied energy

The embodied energy (MJ/kg) of a material is the sum of all the energy required to produce it and as can be seen from Table 9 aerogel has a value, which appears quite favourable in comparison with other conventional insulation materials. In order to provide a fair comparison with these other materials it is necessary to consider the whole life energy cycle analysis. For the purpose of a simple comparison the example used in Section 2.5.3 is considered. Fig. 34 illustrates the thickness of insulation material required for each specimen to achieve the required *U*-value of 0.3 W/m^2 K. Thereafter the future energy savings incurred by the heating of the dwelling are due to the increased thermal resistance of the wall and are therefore taken as being identical. Hence, the difference in the whole life cycle energy is solely the difference in specific embodied energy (MJ/m^2) for the various materials. It can be seen that aerogel in this regard performs favourably against the other conventional materials, with only glass wool having a lower value, being 20 MJ/m^2 lower (10 %). To put this into context against the energy consumed in heating the dwelling, the previous example is once again considered. If a dwelling with walls of this particular thermal resistance was to experience an average internal to external temperature difference of 12 °C, which is typical for a UK winter, then the operational heat loss would amount to 311 kJ/m^2/day. The embodied energy difference is therefore approximately equal to 64 operational winter days of the dwelling.

2.6. Novel materials based on aerogels

Several attempts have been made so far to develop novel products based on aerogel. As discussed previously, *spaceloft* developed by Aspen Aerogels, Inc. (Northborough, MA, US) [23] is a flexible aerogel blanket currently available in thicknesses of 10 mm and has a thermal conductivity of 0.013 W/m K at 273 K, 2–2.5 times lower than traditional thermal insulation materials. Although monolithic silica aerogels are very fragile, Aspen aerogel insulation products which might be prepared by fibres or fibrous materials are textile-like blankets after the gel could be dried. The product might be used to reduce thermal bridges due to studs in wood frame or steel frame building envelopes. The cost of the aerogel was in the range 25€/m^2 or 4000$/m^3 in 2008. This is 10 times higher compared to the traditional insulation materials for the same thermal resistance. It is noted that the aerogel consisted of amorphous silica instead of crystalline silica reduces possible health risks at exposure.

Basogel, the BASF aerogel based on silica, has been developed almost to market readiness over the past few years [139]. The production of *Basogel* is based on a two-stage process starting from the inexpensive materials sodium silicate (water glass) and sulphuric acid. For industrial heat insulation in areas where heating and cooling equipment is used, *Basogel* can help to improve the thermal insulation under atmospheric pressure owing to its low thermal conductivity.

Another aerogel based insulation material called *Nanogel* was developed by Cabot Aerogel (Massachusetts, USA) [23]. At the moment it was only approved for pipe insulation and its thermal conductivity is 0.014 W/m K. *Nanogel* could be activated after it would expand to fill all gaps. An innovative folding technique for the integration of thin monolithic carbon aerogels in button call casings was developed [140]. The performance date of the button cell super-capacitors promise and show almost no degradation after 80,000 charging and discharging cycles.

Washing and aging treatments of silica gels are vital of importance to develop novel materials since they significantly enhance both the permeability and mechanical properties of the wet gels. Unfortunately, scaling-up the process induces severe cracks during supercritical drying [141]. High aging temperature and pressure could promote the dissolution and reprecipitation process of silica and the esterification process of silanols, which will enhance the backbone strength of silica gel, and hence produce silica aerogel with low bulk density, good monolithic performance and hydrophobic features [142]. During washing in water solution a significant increase in the permeability of the gels is observed, showing that dissolution reprecipitation occurs [143].

2.7. Economic assessment of aerogels

Aerogels are still relatively expensive, e.g. the cost of an aerogel window is six times that of conventional double-glazed window [102]. Yingde stated that the cost is nearly £20/m^2 [102,144].

Table 8
Potentials hazardous effects of aerogels on human health [146].

Potential health effects	Explanation
Inhalation	Inhalation of airborne dusts may cause mechanical irritation of the upper respiratory tract
Eye contact	Exposure to dust from this product can produce a drying sensation and mechanical irritation of the eyes
Skin contact	Skin contact with dust from this product can produce a drying sensation and mechanical irritation of the skin and mucous membranes
Skin cbsorption	Material will not absorb through skin
Ingestion	This material is not intended to be ingested (eaten). If ingested in large quantity, the material may produce mechanical irritation and blockage.
Acute health hazards	Dust from this product is a physical irritant, and may cause temporary irritation or scratchiness of the throat and / or itching and redness of the eyes and skin
Chronic health hazards	In 2006, the International Agency for Research on Cancer (IARC) reclassified titanium dioxide as "possibly carcinogenic to humans" (Group 2B) based on animal experiments. In the draft Titanium Dioxide Monograph (Vol. 93), IARC concluded that the human carcinogenic studies "do not suggest an association between occupational exposures as it occurred in recent decades in Western Europe and North America and risk of cancer"
Medical conditions Aggravated by exposure	Excessive inhalation of dust may aggravate pre-existing chronic lung conditions including, but not limited to, bronchitis, emphysema, and asthma. Dermal contact may aggravate existing dermatitis

Table 9
Embodied energy values for different insulation materials [148].

Insulation material	Thermal conductivity (mW/m K)	Density (kg/m^3)	Embodied energy (MJ/kg)
Aerogel	13	100	53.0
EPS	35	30	100.2
XPS	35	30	67.2
Glass wool	36	40	39.4
Cork	45	120	26.3
Foam glass	45	110	27.1
PUR	24	30	101.5
PIR	24	45	101.5

Cost is progressively decreasing: in fact, the global market of aerogels tripled starting from 2003 to 83 M$ in 2008 and is expected to reach up to 646 M$ by 2013 [119]. By extracting alcohol with supercritical CO_2, crack-free aerogels can be obtained at 35 °C and 85 bar [145]. This opens the possibility for a large scale aerogel drying process. It appears that an aerogel plate with a thickness of 1 cm can be dried at a cost of \$2/m^2 and this price will increase exponentially with thickness.

2.8. Toxicity, safety and health issues of aerogels

Silica aerogels are produced by drying aqueous solutions of sodium silicate. They are very light, hydrophobic powders which are effective at lower rates than diatomaceous earths. The very low dust density has prevented the widespread application of these materials in the past because of the potential health hazards which would occur as a result of inhalation. The application of amorphous silica presents a minimal health hazard but inhaled dusts which contain crystalline silica can result in silicosis and other respiratory diseases such as emphysema and pneumoconiosis [145]. Aspen aerogels presented a report about the potential health problems which may be caused by aerogels as shown in Table 8 [146].

2.8.1. Recommendations to avoid health problems caused by aerogels

Aerogels may cause some potential health problems especially during installation. To avoid that, some simple modifications may be performed. As an instance, aerogels may be inserted in rubber, plastic or aluminium covers to prevent them from direct contact with hands. These kind of materials are called *aerobels*. Inhalation during installation may cause mechanical irritation of the upper respiratory tract. Therefore, breath masks should be used and installation should be completed as soon as possible. Protective eyewear and glove should be used in order to avoid eye and skin damage. Airborne dusts during installation may cause some allergic reactions so unless it is compulsory, people with allergy should not stay in the installation environment for a long period of time.

2.9. Predictions for future of aerogels

It is a clear fact that aerogels have extraordinary characteristic features like very low thermal conductivity, translucent structure, good sound insulator etc. However, they need to be more cost effective to compete with the traditional insulation materials. It is understood from the literature that intensive efforts are made to reduce their manufacturing costs and if it is succeeded, aerogels have the potential to be one of the most attractive material of the century. Aerogels have a great deal of application areas such as spacecrafts, skyscrapers, homes, automobiles, electronic devices, clothing etc. With the inevitable needs and developments on the prescribed areas, it is expected that aerogels will be improved and novel high technology materials based on aerogels will be discovered.

2.9.1. Barriers

Initial studies have shown that aerogel blanket can reduce energy consumption from heating or cooling the interior of a fabric structure by 30 to 70%, depending on the climate. It is being used in sports stadiums, recreational facilities, water parks and "green" shopping centres around the world. These are also being used in thermal awnings and blinds to provide a lower cost option to window replacement for retrofits of old buildings that must comply with new energy codes [147].

Aerogel provides greater space efficiency, installation productivity, excellent fire protection, prevents corrosion under insulation and it is also perfect for large scale projects. However it has some of disadvantages such as relatively high cost and brittleness. It is well known that aerogels are one of the most expensive insulation materials. Since aerogels are not highly commercialized yet, they seem unavailable for large scale applications. It is a fact that aerogels are rather fragile, and therefore aerogel applications on huge buildings such as sky scrapers, shopping centres and industrial facilities are seen as costly as well as difficult to apply. Although aerogels have a few difficulties, they have quite benefits and considerable applications. Current studies continued in order to deal with disadvantages as it is mentioned above.

3. Conclusions

In this paper, a comprehensive review on aerogels and their potential applications especially in buildings has been given. It can be easily seen from this study that the aerogels are regarded as one of the most promising thermal insulation materials in the upcoming feature depending due to their superior characteristic features. Moreover the aerogels have the potential for application in a number of environmentally friendly technologies and have the ability to provide notable energy savings. Following points are remarkable for a brief overview of the results:

- Aerogel can provide the best indoor thermal comfort conditions with notably slimmer constructions as a consequence of its superior thermal performance.
- Up to 90% reduction in heat losses through external walls of residential buildings can be achieved with only 20 mm aerogel insulation depending on the fuel type [138].
- Aerogel is also very promising in terms of embodied energy data when compared to other conventional insulation materials. In an example situation where the same overall thermal resistance is considered, it has been shown that Aerogel provides one of the lowest embodied energy values with only glass wool being 10% lower.
- Aerogel can provide much slimmer construction against conventional insulation materials, typically up to 50% less than polyurethane and 70% less than glass wool.
- Aerogel is a key solution to overcome the thermal bridging issues in residential buildings.
- Translucent structure of aerogel enables it to be used not only in facades but also in glazing systems.
- In glazing applications, monolithic aerogel performs better performance compared to granular aerogel because of its better light transmittance.
- Current cost of aerogel is 10 times higher compared to the conventional insulation materials, but future predictions indicate that the unit m^3 price of aerogel will fall below £500 by 2050 as a result of the possible developments in materials science and technology, which results in predomination of aerogel in the market.

Overall, aerogel is an up-and-coming thermal superinsulation material with its superior thermophysical properties and decreasing cost. A great interest in aerogel insulation is expected in the near future especially for the building sector as a consequence of its matchless thermal and acoustic properties. Besides the numerous positive aspects, prospective disadvanteges of aerogel through state-of-the-art information from manufacturers can be useful to identify. Recent contact with the leading aerogel manufacturers in the world has revealed that there are currently two challenging points for aerogel. The first one is the cost which is still notably higher compared to the conventional insulation materials, and the second one is the dust, which occurs during fabrication and is very difficult to eliminate. Manufacturers are trying to make more rigid panels and encapsulations to minimize the dust. Another disadvantage relating to building applications may be experienced in relation to a change in the comfort of the internal environment due to the application of internal insulation with aerogel materials. For instance, under extreme weather conditions such as heat waves, an undesired overheating might be encountered derived from radiation. The level of overheating might also greatly change depending on the building type as reported by Shao et al. in their simulation research [152]. Moreover, greater values of thermal inertia at the building envelope might cause an increment in cooling demand in summer especially for internal wall insulation of aerogel.

It is true that the aerogel is one of the most hydrophobic materials. Due to its hydrophobic feature, it can cause some health hazards on the human body such as emphysema. Therefore people who perform aerogel installation in buildings or any other area must be very careful and follow the relevant health & safety guidelines.

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